“Stability Evaluation of an Opencast Coal Mine with Difficult Ground Conditions: A Case Study”

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In

Excavation Engineering

by

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I, **HITESH KUMAR**, hereby declare that this dissertation titled **"Stability Evaluation of an Opencast Coal Mine with Difficult Ground Conditions: A Case Study"** submitted herein has been carried out by me in the Department of Mining Engineering of Visvesvaraya National Institute of Technology, Nagpur. The work is original and has not been submitted earlier as a whole or in part for the award of any degree / diploma at this or any other Institution / University.

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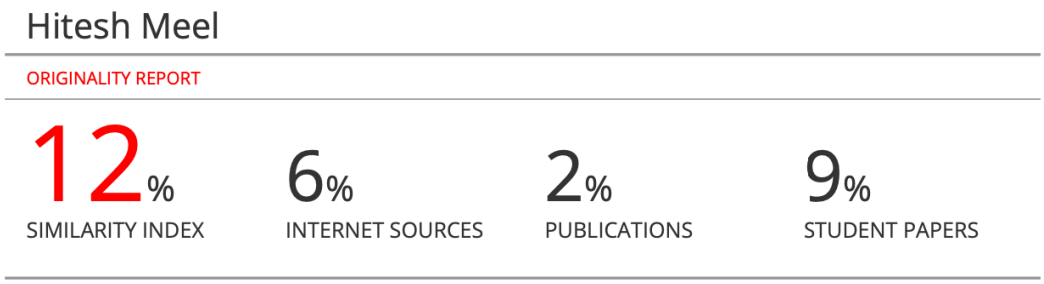

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ABSTRACT

Any nation's ability to grow is reliant on the expansion of its various industries, each of which adds to the GDP of the nation. With a 2.5% GDP contribution, the mining industry is one of the major sectors. In mining, coal is an important and abundant fossil fuel in India and it accounts for 55% of the country's energy needs. The increase in coal production can be largely attributed to the rapid increase in open-cast mining activities and intensified mechanization. This has resulted in the opencast mines going deeper day by day with a maximum stripping ratio of 1:15, at a depth of about 500 m. For any opencast mine, a safe, properly designed, and scientifically engineered slope is essential for the economical, safe, and successful operation.

In this study, the stability evaluation of the pit slope at Bhanegaon Opencast Mine of M/s Western Coalfields Limited (WCL), which is centrally located Coalfields in India has been carried out. The loose and saturated thickness (20 m to 57 m) of the alluvial deposit (mixed with Black Cotton soil and sludge) with Kamthi series formation has high transmissivity which creates a stability problem. In this study, the slope stability analysis has been performed by using the computer program RocScience two dimension (RS2) to assess the effect of difficult ground conditions on stress distribution pattern and safety factor of pit slope. Sections were obtained by Terrestrial Laser Scanner (TLS) and analysed with the help of RS2 software. From the analysis, it was found that the Stress Reduction Factor (SRF) of sections where sand/clay band is present was less (not safe) compared to other working areas because the cohesion of the upper layer material was less.

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1 INTRODUCTION

The majority of the coal production is done through opencast mines in India. Opencast mining is cost-effective mining method allowing a high grade of mechanization and large production. In India, the fast increase in the output of coal can be largely attributed to the rapid increase in opencast mining activities and intensified mechanization(Gupta et al., 2021; Satyanarayana et al., 2017). The production of coal during 2023-24 was 997.83 MT & import was 261.0 MT(Ministry of Coal, Government of India, 2024). India's surface mining industry is expanding quickly in order to close the supply and demand imbalance for coal in the energy sector(Verma et al., 2013). To access the economically valuable minerals beneath the surface, opencast mines require surface excavation as a result the stripping ratio reached 1:15 at 500 meters below the surface which caused the mines to get deeper every day. On a previously plain earth surface, the cut slopes must be formed to begin the excavation process. For safe and profitable mining, the cut slopes' stability is essential(Verma et al., 2011).

Slope stability is a major concern in opencast mines. To ensure safety throughout the mines' lifespan the safe mining operation is the responsibility of mine management. The making of the steepest pit slopes assuming they do not collapse during the mine's life. Therefore, when designing the deep open pit slopes, the design engineer must balance the two opposing components i.e., stability and steepness.

The stability of slopes is very important for safe mining operations. For stability, proper slope design based on the safety factors, correctly dealing with dynamic loading and water problems makes mine stable. The steepening of the slope could cause a slope failure, which would result in lost production, additional stripping costs to remove failed material, bench reforming, haul road rerouting, and production delays. On the other side, Steepening the slopes can result in significant cost savings.

If unsafe conditions are established, the Directorate General of Mines Safety (DGMS) may even decide to close the mine. As such, it is imperative to strike a balance between safety and economics. Consequently, there will be a correspondingly high amount of waste mining and dumping, which greatly increases the risk of highwall and slope failures. Because most production areas are located near the excavation floor, there is a constant risk to the personnel and equipment stationed there, which could result in a catastrophic loss of life and property.

It is necessary to analyse steep slopes thoroughly so that the entire process is safe and profitable. These days, open pits from both large and small-scale industries are unstable because they are reaching greater depths, which is a major concern when designing the slopes. For managing or preventing slope collapse, slope stability analysis and slope monitoring are very important (Kumar et al., 2022). Conventional approaches like limit equilibrium, kinematic analysis, and numerical methods are most frequently used to design slopes. These methods are practical and can be applied to various failure modes (Jayanthu & Veera Reddy, 2011; Satyanarayana et al., 2017).

The limit equilibrium approach can be used to determine the factor of safety for predefined failure modes under homogeneous ground conditions (Sailaja et al., 2021). Limit equilibrium techniques are often used by geotechnical engineers to analyse slope stability. These techniques compute a safety factor, which is the ratio of the available shear strength to the shear stress at equilibrium, with respect to the rock's (or soil's) shear strength. Their primary feature is their simplicity and low parameter count (hydrogeological conditions, geotechnical parameters, geological parameters, and slope geometry). However, complicated issues related to stability in open pit mines are frequently difficult to resolve using limit equilibrium techniques (Fredj et al., 2019; Saadoun et al., 2020). Several authors have worked on the Limit equilibrium method (Bishop, 1954; Durville & Seve, 1996; Faure, 2000; Zhou & Cheng, 2013) but the development of numerical modelling through the Finite Difference, Finite Element, etc. methods give a better understanding of safety factor (Fawaz, 2014).

In this study, the authors have investigated Bhanegaon opencast mine for slope stability purpose.

1.1 BACKGROUND

Bhanegaon opencast mine is situated in the Bina block of Kamptee Coalfields, this coal block falls in the Nagpur District of Maharashtra State (Figure 1). The Bhanegaon Opencast Project is a mine of Western Coalfield Limited (WCL) and situated in the northern part of Nagpur. This Project is located at the confluence of Pench and Kanahan Rivers. There is danger associated during mining operations due to river flowing from three sides of mining area. Considering multi seams and steep gradient of seams which

falls in the range of 1 in 4.5 to 1 in 6, the Horizontal Slicing Method of mining is being used for Bhanegaon OCM (Bina).

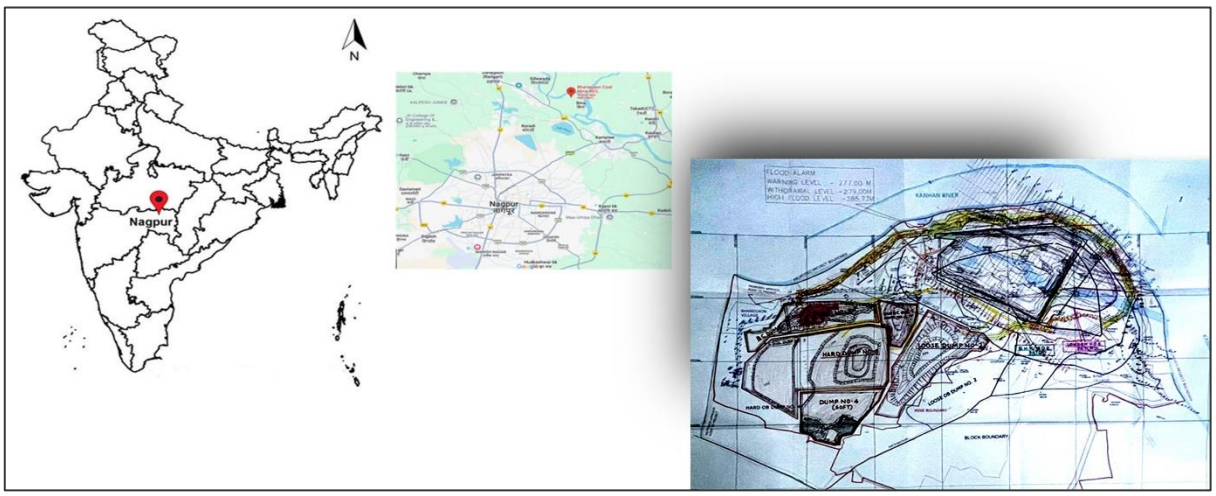

Figure 1.1Bhanegaon Mine Location

All types of Gondwana formation from the Talchir formation of Upper Carboniferous to the Kamthi formation of Upper Permian were encountered in Bhanegaon opencast project area during the geological exploration. The entire block is covered by a thick layer of Alluvium including Black cotton soil and river sand. The loose and saturated thickness (20 m to 57 m) of alluvial deposit (mixed with Black Cotton soil and sludge) with Kamthi formation having high transmissivity may create a stability problem. Currently mine is being worked as per DGMS guidelines and bench profiles are maintained accordingly. Bench geometry for alluvial soil is of 3 m height & 9 m width, for coal is of 10 m height & 10 m width and for rock mass is of 10 m height & 20 m width.

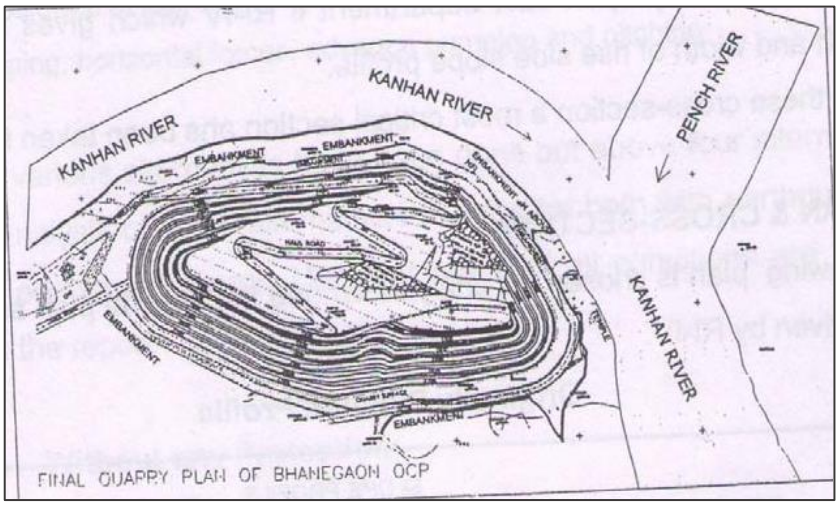

Figure 1.2 Bhanegaon OCM

1.2 OBJECTIVES

The main purpose of this study is to achive the following objectives:

- Stability evaluation of an OCM with difficult ground condition. The site geology comprises an exceptionally thick (20–57 m) loose, saturated alluvial cover (black cotton soils and sludge) overlying Kamthi-series strata – a highly transmissive sequence that has led to severe slope instability concerns.
- Compare geological & geotechnical parameters for stability evaluation.

1.3 SCOPE

The study's primary aim is to evaluate the stability of the main pit slope at the Bhanegaon open-cast coal. The scope includes analyzing the effects of loose, saturated alluvial deposits mixed with Black Cotton soil and high transmissivity Kamthi formation on slope stability.

To analysis slope stability detailed field and laboratory geotechnical investigations (including terrestrial laser scanning of slope profiles) and conducted two-dimensional finite-element slope stability analyses using RocScience RS2 (strength-reduction approach) to determine stress distributions and safety factors for selected slope cross-sections.

It aims to ensure safe and economical mining operations while monitoring and managing ground stability concerns.

1.4 ORGANIZATION OF PROJECT REPORT

Chapter 2: Literature Review

This chapter represents the reviewed work which gives a way ahead- how to proceeds further research work based upon previous literatures around the globe. The aim is to get different ideas for different type of work in different region. This chapter also describes the research gap between the research and scope for the research.

Chapter 3: Field & Laboratory Investigations

This chapter gives detailed description of obtained field data including samples & performed laboratory tests to get geo-mechanical properties of rocks.

Chapter 4: Numerical Modelling

This chapter describes the RS2 software on which the model is developed and procedure for the model preparation is also mentioned along with the final view of modelled section.

Chapter 5: Result & Discussion

This Chapter describes the final results of the above modelled sections considering various conditions with respect to stress and displacement.

Chapter 6: Conclusions

This chapter describes the conclusions based on the above analysis and results of the models under various conditions & its interpretations.

2 LITERATURE REVIEW

A literature review involves the examination of previously published works relevant to a particular research area or field of interest. This process enhances understanding by building upon existing ideas, thereby contributing to the development of both methodological and theoretical frameworks for the current study. Additionally, it helps identify gaps in prior research and outlines potential directions for future investigation related to the present project.

This research is centered on the stability analysis of open cast mines through the application of various advanced software tools. A thorough review of the existing literature facilitates the identification of research gaps and informs the direction of the current investigation.

The summarized discussion of various literature directly or indirectly related to the current project work is mentioned below:

2.1 Design of Optimum Slopes in Opencast Mines including waste dump in Indian Context

The design of optimal slopes in opencast mines is critical for ensuring safety, economic viability, and environmental sustainability. Existing research emphasizes the use of kinematic analysis, limit equilibrium methods (e.g., Bishop's simplified method), and numerical modelling (e.g., UDEC, FLAC) to assess slope stability. These methods evaluate factors such as geological discontinuities, rock mass properties, groundwater conditions, and slope geometry. The Modified Slope Mass Rating (MSMR) system, an extension of Romana's Slope Mass Rating (SMR), has been developed to classify rock masses and guide slope design in Indian opencast mines. (Jayanthu & Veera Reddy, 2011)

Empirical approaches, such as rock mass classification systems (RMR, SMR), are widely used for preliminary slope stability assessments. Case studies in Indian mines (e.g., Nanjankulam, Pandalgudi) demonstrate the application of these methods to design bench heights, face angles, and overall slopes. Regulatory frameworks, such as DGMS rules in India, prescribe maximum bench heights and slopes based on rock type but lack adaptability to complex geological conditions. (Jayanthu & Veera Reddy, 2011)

Recent advancements include integrating slope monitoring technologies (e.g., ground-based radar, microseismic systems) with numerical models to enable real-time stability

assessments. However, most studies focus on large-scale mines, with limited emphasis on small-scale operations or heterogeneous geological settings. (Jayanthu & Veera Reddy, 2011)

The stability of highwall slopes in opencast coal mines is a critical concern, particularly in deep excavations where groundwater and inadequate drainage significantly impact slope integrity. Existing research underscores the use of numerical modeling (e.g., FLAC/SLOPE) to evaluate slope stability under varying hydrological conditions. For instance, Hoek and Bray (1981) established foundational principles for rock slope engineering, emphasizing the role of groundwater in reducing shear strength. Girard and McHugh (2000) highlighted the importance of slope dewatering and monitoring systems to mitigate failures, while Dawson et al. (1999) advanced the shear strength reduction (SSR) technique for calculating factor of safety (FOS) in numerical models. (Satyanarayana et al., 2017)

Recent case studies, such as the Medapalli OCM analysis (Satyanarayana et al., 2017), demonstrate the application of FLAC/SLOPE to assess drained and undrained conditions. Their findings align with Morgenstern (1971), who identified water pressure as a primary destabilizing factor. The study validated numerical results with field data from Cyclops, a real-time monitoring system, which detected precursory displacements before failure. This aligns with Little (2006), who advocated integrated databases for geotechnical data to enhance slope management. (Satyanarayana et al., 2017)

Empirical guidelines, such as Read and Stacey (2009), recommend FOS thresholds for slope scales (e.g., 1.2–1.5 for overall slopes). However, Indian mines often rely on observational methods due to underdeveloped regulatory frameworks. The Medapalli case study exemplifies this gap, where improper drainage led to catastrophic failure despite feasible FOS in drained conditions. (Satyanarayana et al., 2017)

Slope stability of waste rock dumps in opencast coal mines, particularly in dragline-operated mines, is a critical safety and operational challenge. The case study of Jayant Opencast Mine highlights the interplay between steep dump slopes (45°), surcharge loads from over-dumping, hydrological conditions (e.g., water accumulation in slushy interface layers), and seismic activity as primary failure triggers. This aligns with broader research

on dragline dump stability, where improper slope geometry and inadequate drainage are recurrent issues. (Sharma & Roy, 2015)

Existing studies emphasize the role of geotechnical parameters (e.g., cohesion, friction angle) and analytical methods like Fellenius and Bishop's simplified method in assessing Factor of Safety (FoS). The Jayant study validated these methods through back analysis, revealing a pre-failure FoS of 0.94, consistent with field observations. Similar approaches are documented in other Indian mines, where regulatory frameworks often lack specificity for dynamic dragline operation. (Sharma & Roy, 2015)

Internationally, agencies like the National Coal Board (UK) and Mines Branch Canada recommend FoS thresholds (>1.10 for seismic zones), yet practical implementation in heterogeneous dump materials remains challenging. The Jayant case underscores the economic-safety trade-off: steep slopes reduce re-handling costs but increase failure risks, necessitating optimization strategies. Hydrological factors, such as pore pressure from water tables, further compound instability, as noted in analogous studies. (Sharma & Roy, 2015)

The stability of internal dump slopes in opencast coal mines is a critical concern due to the increasing scale of surface mining and the environmental and safety risks posed by slope failures. Existing research emphasizes the use of finite element method (FEM) and strength reduction techniques to assess slope stability, as these approaches avoid assumptions about failure surfaces inherent in traditional limit equilibrium methods. The study demonstrated FEM's efficacy in modeling complex slope geometries and material behaviors. (Verma et al., 2013)

Internal dumping, while economical and environmentally favorable, introduces challenges such as pore pressure buildup from groundwater and seismic risks. The Mohr-Coulomb model, widely used for dump materials, provides a framework for analyzing shear strength parameters. However, study highlights the limitations of assuming uniform material properties in heterogeneous dump compositions. (Verma et al., 2013)

The Wardha Valley analysis builds on global practices, such as benching to enhance stability, as recommended by Janbu (1968) and Spencer (1967). However, while benching improves FOS, the study confirms that increasing dump height (>80m) significantly reduces stability, consistent with findings in Chilean mines. Regulatory frameworks, such

as those by ISRM, provide material testing standards but lack guidelines for dynamic or site-specific dump designs, a gap evident in Indian mining practices. (Verma et al., 2013)

The stability of open-pit mine slopes is a critical concern in mining engineering, particularly in regions with complex geological and hydrological conditions. The study on the Wardha Valley Coalfield exemplifies the application of Slope Mass Rating (SMR) and kinematic analysis for evaluating slope stability. Building on Romana's (1985) SMR system, the study classifies rock masses into stability classes based on structural discontinuities, groundwater conditions, and excavation methods. This aligns with foundational work by Bieniawski (1974) on Rock Mass Rating (RMR) and Hoek & Brown's (1988) geological strength index (GSI), which emphasize the role of rock mass quality in slope design. (Verma et al., 2011)

Kinematic analysis using stereonet plots, as demonstrated in the study, is a well-established method for identifying potential failure modes (planar, wedge, toppling) by analyzing the geometric relationship between joints and slope faces. Similar approaches have been validated in other coal fields, such as Jharia, where structural discontinuities and weathering significantly influence stability. The integration of field observations with empirical classifications (e.g., RQD, UCS) further underscores the importance of site-specific geotechnical data in fire-prone mines. (Verma et al., 2011)

Slope stability in open pit mines is a critical concern due to its direct impact on safety, economics, and operational efficiency. Existing research emphasizes the role of geological discontinuities (e.g., faults, joints) and bench design parameters (slope angle, height) in destabilizing slopes. Traditional empirical methods, such as limit equilibrium analysis and design charts for predefined failure modes (plane, wedge, circular), have been widely used but are limited to homogeneous conditions and simple geometries. Numerical modeling tools like Slide software have emerged to address complex scenarios by incorporating rock mass properties and discontinuities. Study highlights the factors such as groundwater, lithology, and dynamic forces further influence stability, with slope angles >40° and bench heights >25m often leading to safety factors <1.0. Recent work reinforces these findings, demonstrating that numerical modeling can provide tailored guidelines for slope design under varying geological conditions. However, most studies focus on static analyses, neglecting time-dependent variables like weathering or seismic activity, and assume idealized rock mass homogeneity. (Shailaja et al., 2021)

Slope stability in opencast mines is a multidisciplinary challenge influenced by geological, geotechnical, and operational factors. Traditional empirical methods, such as limit equilibrium analysis, provided foundational insights but are limited to homogeneous conditions and predefined failure modes. Numerical modeling tools like Slide software have advanced the field by simulating complex geometries and discontinuities, revealing critical thresholds for slope angles and bench heights that reduce safety factors. (Kumar & Kumar M, 2022)

Geological structures, such as faults, joints, and bedding planes, dictate failure modes (plane, wedge, circular) and interact with groundwater to exacerbate instability. Geotechnical parameters like cohesion, internal friction angle, and shear strength are equally critical, with lower values increasing failure risks. Slope geometry-particularly bench height, width, and overall angle-directly impacts stability, with steeper slopes accelerating shear stress accumulation. Modern advancements, such as IoT and wireless sensor networks (WSN), enhance slope monitoring but often lack multi-sensor integration to address multifaceted failure triggers. (Kumar & Kumar M, 2022)

The stability of waste dump slopes in open-pit mines is a critical concern due to their economic, environmental and safety implications. Existing research emphasizes the role of geotechnical parameters (e.g., cohesion, friction angle), slope geometry (e.g., bench height, overall slope angle), and external factors (e.g., pore water pressure, seismic activity) in influencing stability. Numerical modeling, particularly the Strength Reduction Method (SRM) integrated into tools like FLAC, PLAXIS, and Phase2, has become a cornerstone for analyzing complex slope behaviors, enabling automatic identification of critical slip surfaces and stress-strain distributions. (Gupta et al., 2021)

Geotechnical and Geometrical Factors like Cohesion and friction angle significantly impact stability, with friction angle being the most sensitive parameter Steeper slopes (>40°) and taller benches (>25m) reduce safety factors (FoS), while heterogeneous materials (e.g., soil-rock mixtures) enhance stability compared to homogeneous soils. Hydrological Effects like Pore water pressure from rainfall or groundwater infiltration reduces shear strength, with prolonged saturation leading to catastrophic failures. Horizontal drains and improved drainage systems mitigate these effects. Blasting vibrations and earthquakes exacerbate instability by increasing shear stress, particularly in heterogeneous slopes. Weak foundations or interfaces between dump material and bedrock

are primary failure triggers, often exacerbated by poor compaction or clay layers. (Gupta et al., 2021)

2.2 Optimization of Slope Design in Opencast Mines in Global Contexts

Slope stability in quarries and open-pit mines has been extensively studied using empirical, analytical, and numerical approaches. Empirical methods, such as RQD, RMR and SMR classifications, provide rapid assessments of rock mass quality but often overlook dynamic factors and localized weaknesses. Analytical methods like the limit equilibrium method (LEM), implemented in tools such as Slide 6, are widely used for calculating safety factors but struggle with complex geometries. Numerical methods, including finite element (Phase2) and finite difference (Flac) modeling, address these limitations by simulating stress redistribution and dynamic effects, such as blasting vibrations and groundwater infiltration. (Saadoun, 2020)

The study on the Chouf Amar quarry exemplifies a multi-method approach, integrating empirical classifications, kinematic analysis, and numerical modeling to assess stability. Their findings reveal that while the full quarry profile appears stable, marl interlayers significantly reduce safety factors under wet and dynamic conditions. This aligns with prior research emphasizing the destabilizing role of weak lithologies and blasting effects. However, the study highlights a critical limitation of LEM in detecting thin marl layers, underscoring the superiority of numerical methods for such scenarios. (Saadoun, 2020)

Numerical modeling has become a cornerstone in slope stability analysis, offering insights into complex interactions between geological, geotechnical, and operational factors. Traditional limit equilibrium methods (LEM), while simple, often fail to capture intricate stress redistributions or dynamic conditions (Duncan & Wright, 2005). The advent of numerical methods like finite element (FEM) and finite difference (FDM) modeling, combined with the Shear Strength Reduction (SSR) technique, has enabled more robust analyses of slope behavior, including stress-strain distributions and failure mechanisms. Studies by Yingren & Shangyi (2004) and Zheng et al. (2009) demonstrated the SSR method's efficacy in identifying critical slip surfaces without predefined failure modes. (Fredj, 2019)

Comparative studies of geotechnical software, such as FLAC, PLAXIS, and Phase2, reveal their strengths in simulating slope stability under varying conditions. For instance, Fredj et al. (2019) compared these tools in an Algerian phosphate mine, finding consistent safety factors (SF ≈ 0.84–0.87) across all platforms but divergences in plastic zone predictions. Their work aligns with prior research emphasizing Phase2's reliability in correlating shear strain localization with plasticity indicators. However, such studies predominantly focus on static, homogeneous models under idealized geological conditions, often overlooking dynamic environmental interactions or material heterogeneity. (Fredj, 2019

2.3 Finite Element Method

Finite Element Method (FEM) is one of the numerical methods used for accurate solution of engineering problem that are simple or complex by nodal solution. The FEM has capacity to discretize problem and analyze it part to part. The basic idea associated with FEM that it will find the solution of complex problem by converting it into simple problem irrespective of geometry of the problem. FEM is a technique in which given domain is consider as a collection of simple domains known as "Finite elements" with proper mesh refinement. (Erhunmwun & Ikponmwosa, 2017)

In FEM, the nodes and elements are two important aspects in which elements is that when one can divide model into small pieces and these elements connects all characteristics points known as nodes. Uses of piecewise continuous functions over triangular region is involved in the FEM.

The Step- by- Step procedure for the solving problem using FEM is as follows:

1. Establishing governing equations and boundary conditions
2. Discretization of Domain
3. Determine the element of equations
4. Assemble global equations
5. Imposition of boundary conditions of the problem
6. Solution of global equation
7. Presentation of results

As FEM is very versatile method, it is use to solve problems related to the Digital computer and programming languages, solve sets of differential equations in mathematics, in fluid mechanics for similarity approach, perturbation method, integral methods and characteristics methods, structural engineering and aeronautical engineering.

FEM has various advantages like:

1. A body analysed should be of various shapes, load and support conditions.
2. Matrix mesh can mix elements of different types.
3. Its versatility can be contained in the single program.
4. Actual structure and its finite element model are very similar.
5. Accuracy of results is very high.

Numerical modeling facilitates the examination of complex mechanisms and interdependencies among variables, significantly improving system understanding. However, addressing such multifaceted challenges typically involves multiple labor-intensive stages that demand considerable time and effort. To alleviate this burden, engineers would greatly benefit from a dedicated software tool designed to streamline workflows and simplify task execution.

2.4 RS2 Software: History, Features, Advantages & Significance in development of Model for Slope Stability

In 1990, RS2 named as the "PHASE" which is DOS operated program system and known as primitive software for this program. Nine years later, in 1999 this phase DOS evolved or undergo some modifications and converted into "Phase 2" which is windows operating system based. After so many evolutions "version 6" is introduced in 2005. This version 6 involved "static Finite Element Groundwater Analysis". In 2008, "Phase 2" again evolved and introduce advanced version 7-8 which includes "Transient Groundwater Analysis". The name "Phase 2" changed into "RS2" in 2015 which leads to the version 9 of this software. The most recent version 11 is released in May 2020 which is known as modern version of RS2 software. The detail information about new version of RS2 is mentioned below:

Rocscience software is an example of software created by combining expertise with the most modern breakthroughs in underground analysis and computer technology. As a result, Rocscience software was utilised to model the subsurface workings in this investigation. As a result, Rocscience software was utilised to model the dam structure in this study.

For soil and rock applications, Rocscience (RS2) is a sophisticated 2D finite element tool. RS2 is a general-purpose finite element analysis tool (RS2 = Rock and Soil 2-dimensional analysis programme). RS2 is a finite element analysis programme for tunnel and support

design, underground excavations, surface excavations, excavation design, slope stability, embankments, dynamic analysis, foundations, and probabilistic analysis, as well as consolidation, dynamic analysis, groundwater seepage, and more. Each part is divided into tiny triangles (mesh) for numerical modelling using the finite element approach, which covers the maximum area of the section and produces highly precise results. Each small triangle is graded evenly and is regarded to have three nodes.

Features of RS2

New features which are included in RS2 software in version 11 are

1. Constant groundwater boundary conditions
2. Verification models are included.
3. Recomputation of model is possible from older to recent version.
4. Automatic ponded water load for free surface.
5. Warning for no restrained conditions.
6. Option for results visualization and report in RS2 interpretation.

Due to these advance features included in RS2 software, it is used nearly in 76 countries around the world and in 512 institutes.

Advantages of RS2

1. It is use for civil as well as mining projects.
2. It is use for structures above and below ground.
3. It enables to analyse stress and deformation effectively.
4. It is used to evaluate the stability of structure.
5. It helps to design supports and staged excavation with ease.

RS2 Significance in development of Model for Slope Stability

Its significance in developing a slope stability model lies in its ability to provide a realistic, detailed, and integrated understanding of the geomechanical behavior of slopes under various conditions. Key Significances:

1. Advanced Stress-Strain Analysis

RS2 allows for the modeling of complex stress-strain relationships in soils and rocks using both linear and nonlinear constitutive models (e.g., Mohr-Coulomb, Hoek-Brown,

Hardening Soil). This is essential for realistic simulation of slope behavior, especially under critical loading or failure conditions.

2. Modeling Complex Geometries and Heterogeneities

It can model irregular geometries, discontinuities, stratification, and material interfaces—features commonly encountered in real-world slope conditions, especially in mining contexts.

3. Support System Integration

The software supports modeling of various support systems (e.g., anchors, shotcrete, retaining walls), helping in the design and assessment of stabilization techniques for potentially unstable slopes.

4. Strength Reduction Method (SRM)

RS2 applies the Strength Reduction Method to compute the Factor of Safety (FoS). This method systematically reduces shear strength parameters (cohesion and friction angle) until failure occurs, offering a more accurate and continuous stability assessment than traditional limit equilibrium methods.

5. Time-dependent and Dynamic Analysis

It facilitates creep, time-dependent deformation, and even dynamic analysis (e.g., earthquake loading), which are vital for evaluating long-term and transient slope behavior.

6. Integration with RSData and Other Rocscience Tools

RS2 can work in conjunction with RSData for lab test interpretation, and with Slide2/Slide3 for cross-verification with limit equilibrium analysis, enhancing model reliability.

RS2 plays a critical role in the development of slope stability models by enabling a comprehensive, realistic and detailed finite element analysis. It surpasses conventional methods by integrating multiple physical processes and geotechnical behaviors, making it an indispensable tool for safe and cost-effective slope design, especially in mining and infrastructure projects.

The design of optimum slopes in opencast mines is a critical component for ensuring safety, economic efficiency, and environmental sustainability. In the Indian context, slope design primarily employs empirical (RMR, SMR, MSMR), analytical (limit equilibrium methods), and numerical techniques (FLAC, UDEC, Slide) to address challenges posed by complex geology, hydrology, and operational conditions. Studies from Indian coalfields (e.g., Medapalli, Jayant, Wardha Valley) emphasize the influence of groundwater, dump height, and dynamic factors such as blasting and seismicity on slope stability. Despite advances in numerical modeling and real-time monitoring (e.g., Cyclops), the regulatory framework often remains static, particularly for small-scale and heterogeneous sites. Internationally, research has advanced through integrated methodologies combining empirical, kinematic, and numerical approaches, with FEM and SSR techniques offering detailed insights into stress redistribution, critical slip surfaces, and dynamic interactions. Global studies (e.g., Chouf Amar quarry, Algerian phosphate mines) confirm the limitations of traditional LEM in capturing localized instabilities and highlight the superiority of advanced numerical tools like FLAC, PLAXIS, and Phase2 in simulating complex geological conditions. Collectively, these studies underscore the need for adaptive, site-specific, and technology-driven slope design strategies in both Indian and global mining practices.

2.5 RESEARCH GAPS

After conducting literature review on slope stability analysis, a number of research gaps have been identified and analyzed. They are as follows:

Dynamic Multi-Physics Coupling in Numerical Models: Existing studies (e.g., Saadoun et al., 2020; Fredj et al., 2019) rely on static or simplified dynamic analyses, neglecting coupled interactions between transient pore pressure (rainfall infiltration), seismic vibrations, and blasting-induced stresses. A critical gap exists in developing coupled hydro-mechanical-seismic models to simulate real-time slope responses under dynamic loading, integrating sensor data (e.g., IoT-based piezometers) for adaptive stability updates.

Multi-Scale Heterogeneity and Anisotropy in Waste Rock: Current numerical frameworks (e.g., FLAC, Phase2) homogenize dump materials, failing to capture the anisotropic behavior of soil-rock mixtures, weak interlayers (e.g., marl-clay interfaces), or spatially

variable fracture networks. Advanced micromechanical-stochastic models are needed to simulate grain-scale interactions (e.g., rock block effects in soil matrices) and predict emergent macro-scale failures, as highlighted by Gupta et al. (2021).

Time-Dependent Chemo-Mechanical Degradation: While studies (Sailaja et al., 2021; Gupta et al., 2021) acknowledge weathering, they lack predictive models for long-term degradation mechanisms, such as cohesion loss in marl due to cyclic wetting-drying or sulfate-induced weakening in dump foundations. A gap exists in coupling geochemical weathering processes (e.g., mineral dissolution) with mechanical strength reduction over decades of exposure.

AI-Driven Predictive Analytics for Failure Precursors: Traditional numerical methods (e.g., SRM) require manual calibration and predefined failure modes, limiting their predictive capability. Leveraging machine learning (ML) to automate parameter inversion (e.g., friction angle from LiDAR displacement data) or deep learning for real-time instability detection (e.g., correlating acoustic emissions with shear band formation) remains unexplored, despite its potential to enhance early warning systems.

Unified Stability Criteria for Geologically Diverse Settings: Current guidelines (e.g., slope angles ≤40°) are empirically derived from localized case studies (e.g., Gupta et al., 2021; Zhan et al., 2018) and lack universal applicability. A systematic framework is needed to establish region-specific stability thresholds that account for variable lithologies (e.g., igneous vs. sedimentary bedrock), climatic regimes (arid vs. tropical), and operational practices (e.g., dump construction methods), validated through multi-site numerical benchmarking.

These research gaps address both methodological limitations (e.g., model oversimplification) and operational challenges (e.g., adaptive monitoring), positioning the thesis to advance slope stability science with actionable, field-reliable solutions.

3 FIELD & LABORATORY INVESTIGATIONS

For this project Bhanegaon Open Cast Mine was visited and mine profile, geology & working methodology was inspected. Coal & Sandstone samples were collected from field for laboratory investigations along with mine bench profile, bore hole sections & piezometric data. Details of Field & Laboratory investigations are as follows:

3.1 FIELD INVESTIGATIONS

Bhanegaon Open Cast Mine is situated at the confluence of the Pench and Kanhan rivers. The area is characterized by a loose and saturated alluvial deposit ranging in thickness from 20 to 57 meters comprising a mix of black cotton soil and sludge. This, combined with the high transmissivity of the underlying Kamthi Formation, may pose significant slope stability challenges.

3.1.1 GEOLOGY

All types of Gondwana formation from Talchir Formation of Upper Carboniferous to Kamthi Formation of Upper Permian were encountered in Bhanegaon OCM area during the geological Exploration. The entire block is covered by thick layer of Alluvium including Black cotton soil and river sand. The geology of the area is described below:

***Talchir Formation*:** This formation, consisting of green shale and fine-grained sandstone, is not exposed in the block but it has been intersected in one borehole within the block.

***Barakar Formation*:** The Barakar formation which contains the coal seams overlies Talchirs conformably with a gradational contact. The total column of Barakar can be broadly divided into three units, i) the upper 35-80 m of strata of medium to coarse grained sandstone and shales, but devoid of coal seams ii) the middle 110-123 m of strata containing the five coal horizons and iii) the lower horizon of about 100 m of fine grained garnetiferous sandstone, shale and thin bands of coal, but devoid of any seams of workable thickness.

***Motur Formation*:** Motur Formation overlies the Barakars conformably and is characterized by the greenish chloritic medium grained sandstone with intermittent beds of variegated clay/shale. Maximum thickness of this formation encountered in southern part of the block is 220.75 m in one of the boreholes.

***Kamthi Formation*:** The Kamthis have been found to overlap the underlying formations unconformably and are represented by yellowish brown medium to coarse grained ferruginous sandstones, shale and clay. Kamthis have been intersected in 10 boreholes as a thin capping.

Soil/Alluvium: Alluvium in this block consists of black cotton soil followed by loose sand with pebbles. The entire block is covered by a thick layer of this formation.

***Geological Structure*:** The Bina block under report is generally covered by a thick layer of black cotton soil and loose sand with pebbles (alluvium) followed by a blanket of Kamthis. None of the geological formations are actually exposed on the surface in the block. The geological structure is therefore based on the subsurface data generated from boreholes.

Table 3.1 Geological Succession of Kamptee Coalfield

Age	Formation	Thickness range (m)		Lithology
		Minimum	Maximum	
Recent to sub-recent	Alluvium/ Weathered Mantle	18.0 (CMKB-1)	61.00 (NCKMB-4)	Black cotton soil, clay, river sand & boulders
---------- Unconformity ----------				
Upper Permian	Kamthi	2.30 (CMKB-4)	42.53 (NCKMB-9)	Reddish pink medium and coarse grained ferruginous sandstone.
---------- Unconformity (overlap)----------				
Middle Permian	Motur	11.90 (NCKMB-26)	220.75 (NCKMB-2)	Green chloritic clays, grey, variegated clays, sandstone with thin coal/carb.streaks
Lower Permian	Barakar	22.50 (CMKB–15)	214.83 (KMT-7)	Dirty white, light grey fine to coarse grained feldspathic sandstone with shale, carb. Shale and coal seams
Upper Carboniferous	Talchir	19.48 (KMT-7)		Fine grained greenish sst. and greenish shale.
----------Unconformity ----------				
Archaeans	Metamorphics	Not encountered		Schists and gneisses

***Strike and Dip of Strata*:** The strike of the beds in the block is generally NW-SE and dips are 9°to 14° due SW with gradient ranging from 1 in 4 to 1 in 6.

***Surface feature and precautions*:** Bina block is generally level country with the gentle slope towards the north. The surface elevation varies from 287 m above MSL in the central part to 277 m along the bank in north. Most part of the block is above HFL. Embankment of sufficient height and width at the top against bank rivers is made as additional precaution. Southern east boundary of the mine is in proximity of the Bina village, which is located in dip side of the quarry. It is at safe distance of about 150m from the dip side of quarry surface.

Faults: The Bina block is traversed by four faults and are serially numbered as F1, F2, F3 & F4. Due to thick overlapping cover consisting of Soil and Kamthis, none of the faults are traceable on the surface. Total 4 nos. of faults that have been interpreted in the block with throw ranging from 10 to 40 m. However only two faults viz. fault F1-F1, F2-F2 occur within the quarriable area.

Presence Of Intrusives: The block is devoid of any intrusive dykes or sills. As such the seams in the block are not heat effected.

***Sequence of Coal Seams & Parting*:** The complete set of 5 seams (i.e., Seam I to Seam-V), as correlated in adjacent blocks, exists in Bina block also. These seams are confined to the Middle Barakar strata. Out of 8 split sections of the 5 correlatable seams only 7 horizons viz. V, IV (Top), IV (Middle), IV (Bottom), III, II (Top) & II (Bottom) have attained potentiality. Seam I is not workable in this block. For the purpose of seam delineation, coal and shaly coal have been considered as part of the seam. Bands have been included in the seam when their thickness is equal to or less than coal / shaly coal horizon immediately underlying/overlying the band. Occurrence of all the five correlatable coal seams of the Kamptee Coalfield has been established by drilling in Bina Block. The column between the floor of oldest seam and the Barakar/Talcher contact is termed as Lower Barakar.

The Seam-V has developed workable thickness all over the Bina Block. Seam V was intersected in 35 boreholes where the thickness ranges from 6.47 (KMT-3) to 11.19m (NCKMB-23). The parting with Seam IV (Top) varies from 20.84 m (NCKMB-5) to 32.96 m (NCKMB-26).

The Seam-IV (Top, Middle & Bottom) has attained workable thickness throughout the Block. Seam IV(Top) was intersected in 36 boreholes where the thickness ranges from 1.01 (NCKMB-1I) to 4.36 (NCKMB-1), Seam IV(Middle) was intersected in 40 boreholes where the thickness ranges from 0.86 (KMT-9) to 3.88 (NCKMB-11) & Seam IV(Bottom) was intersected in 45 boreholes where the thickness ranges from 1.20 (NCKMB-1) to 4.06 (NCKMB-8). Seam IV(Bottom) was intersected in 45 boreholes where the thickness ranges from 1.20 (NCKMB-1) to 4.06 (NCKMB-8). The parting with Seam III varies from 17.10 m (CMKB-8) to 30.91 m (NCKMB-4).

The Seam-III has attained workable thickness throughout the Block. Seam III was intersected in 46 boreholes where the thickness ranges from 1.97 (KMT-12) to 6.15 (NCKMB-10). The parting with Seam II(Top) varies from 9.23 m (NCKMB-21) to 32.93 m (NCKMB-22A).

The Seam-II (Top & Bottom) has attained workable thickness throughout the Block. Seam II(Top) was intersected in 44 boreholes where the thickness ranges from 1.60 (KMT-3, NCKMB-2) to 4.35 (CMKB-14) & Seam II(Bottom) was intersected in 46 boreholes where the thickness ranges from 1.20 (CMKB-8) to 3.95 (KMT-16). Parting with Seam-I varies from 4.10 m (NCKMB-4) to 12.75 m (NCKMB-9).

The Seam-I has developed workable thickness only in isolated patches in Bina Block. Seam I was intersected in 28 boreholes where the thickness ranges from 0.30 m. (CMKB-11) to 1.80 m (CMKB-4).

Table 3.2 Sequence of Seams and their Intervening Partings

Seam/ Sections	Depth Range		Strategraphic Thickness (m)		
	Minimum	Maximum	Minimum	Maximum	Prelevant
Seam V	26.20 (NCKMB-15)	121.90 (NCKMB-14)	3.05 (NCKMB-15)	11.17 (CMKB-2)	6.47 to 9.85
Parting			20.84 (NCKMB-5)	31.11 (KMT-3)	
Seam-IV Top	32.30 (CMKB-4)	155.00 (NCKMB-26)	1.05 (NCKMB-10)	3.35 (NCKMB-8)	1.20 to 1.50
Parting			2.17 (NCKMB-10)	7.70 (CMKB-11)	
Seam IV Middle	32.90 (CMKB-6)	160.32 (NCMKB-26)	1.14 (KMT-16)	3.41 (NCMKB-5)	1.90 to 2.20
Parting			3.79 (NCKMB-7)	8.20 (NCKMB-10)	
Seam IV B	25.60 (CMKB-9)	168.32 (NCKMB-26)	1.77 (KMT-07)	4.06 (NCMKB-08)	2.70 to 3.30
Parting			18.65 (NCKMB-15)	24.20 (CMKB-9)	
Seam-III	34.07 (NCMKB-12)	190.28 (NCKMB-14)	1.90 (NCKMB-25)	6.15 (NCKMB-10)	3.5 to 4.50
Parting			9.60 (CMKB-9)	23.74 (KMT-3)	
Seam-II Top	38.90 (CMKB-5)	217.10 (NCKMB-14)	1.60 (KMT-3)	3.55 (NCKMB-10)	2.80 to 3.20
Parting			0.58 (NCKMB-7)	3.90 (CMKB-13)	
Seam-II Bottom	25.50 (CMKB-15)	221.71 (NCKMB-14)	0.92 (B-6)	3.95 (KMT-16)	2.75 to 3.15
Parting			8.65 (NCKMB-12)	12.30 (CMKB-15)	
Seam-I			0.30 (CMKB-11)	1.80 (CMKB-4)	Workable in isolated patches

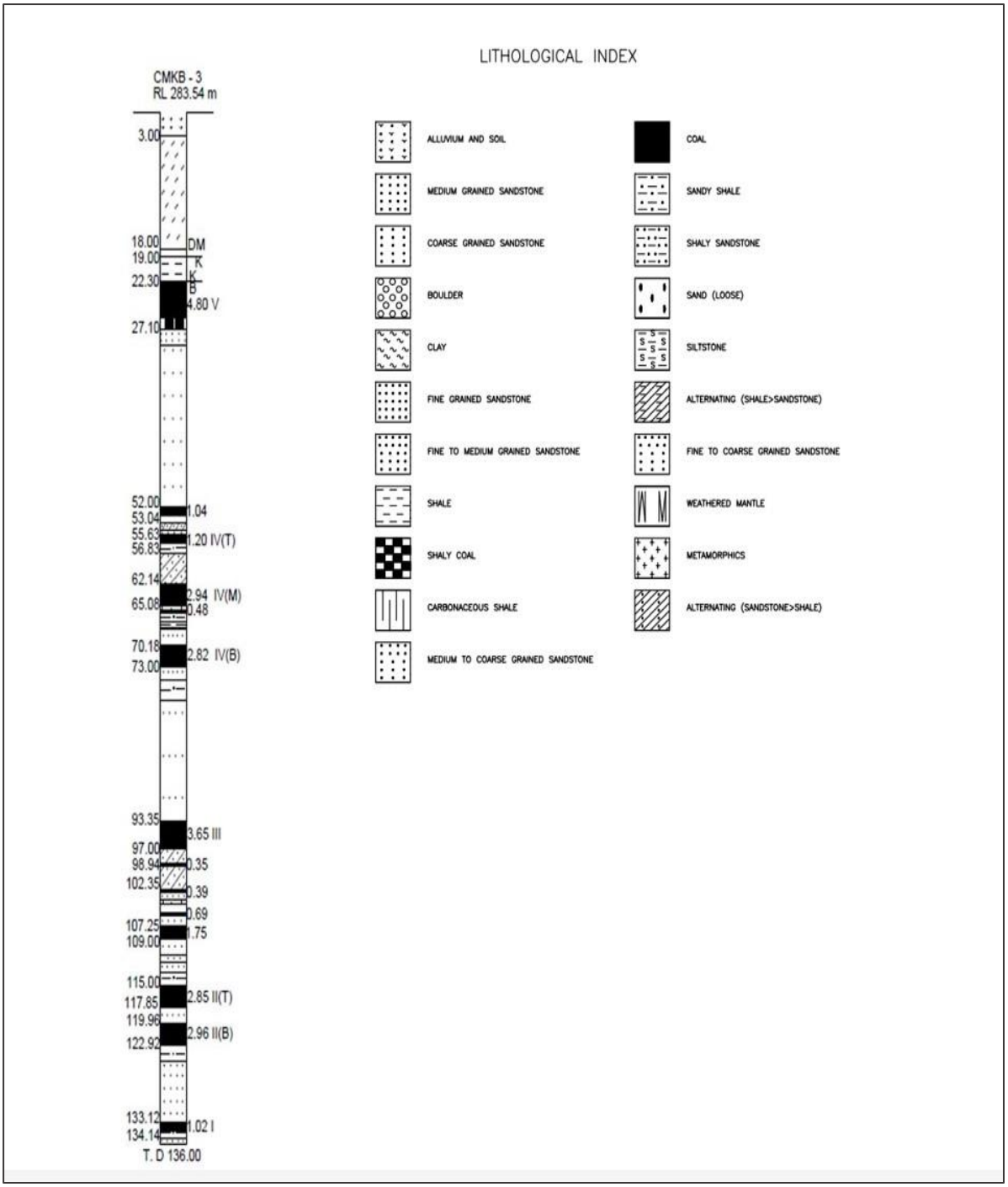

Figure 3.1 CMKB-3 Lithological Index

3.1.2 HYDROGEOLOGY

The Bhanegaon OCM area is located near the confluence of Pench and Kanhan rivers. The Kamthi Formation along with Alluvial deposit (loose sand) represents the Shallow Aquifer. The thick bed of alluvium and current bedding seen in the mine cutting of nearby

Gondegaon OCM, located opposite bank of Kanhan river, is indicative of recent alluvial deposition. Barakar Formation along with coal seam is lying below the Kamthi Formation/ Motur Formation represents the Deeper Aquifer in the study area. The Motur Formation is greenish, chloritic medium-grained sandstone with intermittent beds of variegated clay/shale. The yield of the formation is very poor and aquifer composed of this formation is very less in potential.

The drainage of the area is mainly controlled by the easterly flowing Kanhan River & Pench Rivers. The confluence of these two rivers is located just northeast of the block. A few seasonal nallahs originate within the block and drain in to the Kanhan River. The HFL is 285 m.

The Bina Geological Block is mostly covered with soil and alluvium underlain by Kamthi and Barakar sequence of formations. Ground water occurs below the water table in sand horizons of alluvium and sandstone and its secondary porous structures in semi consolidated Gondwana formations. Ground water exists in the mine area under both confined/semiconfined and unconfined conditions. Unconfined aquifer extending down to a depth of about 25 m below ground level (bgl) occurs in alluvium, whereas the confined / semiconfined aquifer would be encountered at greater depths in Kamthi and Barakar formations.

In respect of unconfined aquifer, depth of water table varies from 8.0 m to 12.0 m bgl in post monsoon season and it attains deepest level in premonsoon months. The water table fluctuation between the two extreme seasons varies from 2.0 m to 5.0 m. The water table elevation ranges between 270 m and 283 m above MSL in pre-monsoon period. Ground water flow direction inferred to be towards east in Bina block. The hydraulic gradient is around 3.8 x 10-3 to 9.2 x 10-3. Generally, ground water flows from recharge area to discharge zone. The effluent nature of the Kanhan river flowing in the north and east of the area corroborates the flow direction.

A Piezometer (Device id F23-0070, Bore 1) has been installed at check post, Bhanegaon OCM for continuous monitoring of ground water level and its pressure. Piezometric data were collected to establish water table for this project. Collected data for three months (April, may & June) including peak monsoon are summarized in the Table 3.1. Average depth of water table is 20.45 m based on these data.

Table 3.3 Piezometric Data

Date	Water Table(m)	Date	Water Table(m)
01/04/2024-08:00 am	21	01/05/2024-08:00 am	20.8
01/04/2024-08:00 pm	21	01/05/2024-08:00 pm	20.7
02/04/2024-08:00 am	21	02/05/2024-08:00 am	20.7
02/04/2024-08:00 pm	21	02/05/2024-08:00 pm	20.7
03/04/2024-08:00 am	21	03/05/2024-08:00 am	20.7
03/04/2024-08:00 pm	21	03/05/2024-08:00 pm	20.7
04/04/2024-08:00 am	21	04/05/2024-08:00 am	20.7
04/04/2024-08:00 pm	21	04/05/2024-08:00 pm	20.7
05/04/2024-08:00 am	21	05/05/2024-08:00 am	20.7
05/04/2024-08:00 pm	21	05/05/2024-08:00 pm	20.7
06/04/2024-08:00 am	21	06/05/2024-08:00 am	20.6
06/04/2024-08:00 pm	21	06/05/2024-08:00 pm	20.7
07/04/2024-08:00 am	21	07/05/2024-08:00 am	20.7
07/04/2024-08:00 pm	21	07/05/2024-08:00 pm	20.6
08/04/2024-08:00 am	21	08/05/2024-08:00 am	20.6
08/04/2024-08:00 pm	21	08/05/2024-08:00 pm	20.6
09/04/2024-08:00 am	21	09/05/2024-08:00 am	20.6
09/04/2024-08:00 pm	21	09/05/2024-08:00 pm	20.6
10/04/2024-08:00 am	21	10/05/2024-08:00 am	20.6
10/04/2024-08:00 pm	21	10/05/2024-08:00 pm	20.6
11/04/2024-08:00 am	21	11/05/2024-08:00 am	20.5
11/04/2024-08:00 pm	21	11/05/2024-08:00 pm	20.5
12/04/2024-08:00 am	21	12/05/2024-08:00 am	20.5
12/04/2024-08:00 pm	21	12/05/2024-08:00 pm	20.5
13/04/2024-08:00 am	21	13/05/2024-08:00 am	20.5
13/04/2024-08:00 pm	21	13/05/2024-08:00 pm	20.5
14/04/2024-08:00 am	21	14/05/2024-08:00 am	20.5
14/04/2024-08:00 pm	21	14/05/2024-08:00 pm	20.5
15/04/2024-08:00 am	21	15/05/2024-08:00 am	20.5

15/04/2024-08:00 pm	21	15/05/2024-08:00 pm	20.5
16/04/2024-08:00 am	21	16/05/2024-08:00 am	20.5
16/04/2024-08:00 pm	21	16/05/2024-08:00 pm	20.5
17/04/2024-08:00 am	20.9	17/05/2024-08:00 am	20.4
17/04/2024-08:00 pm	21	17/05/2024-08:00 pm	20.5
18/04/2024-08:00 am	20.9	18/05/2024-08:00 am	20.4
18/04/2024-08:00 pm	21	18/05/2024-08:00 pm	20.4
19/04/2024-08:00 am	20.9	19/05/2024-08:00 am	20.4
19/04/2024-08:00 pm	20.9	19/05/2024-08:00 pm	20.4
20/04/2024-08:00 am	20.9	20/05/2024-08:00 am	20.4
20/04/2024-08:00 pm	20.9	20/05/2024-08:00 pm	20.4
21/04/2024-08:00 am	20.9	21/05/2024-08:00 am	20.4
21/04/2024-08:00 pm	20.9	21/05/2024-08:00 pm	20.4
22/04/2024-08:00 am	20.9	22/05/2024-08:00 am	20.3
22/04/2024-08:00 pm	20.9	22/05/2024-08:00 pm	20.3
23/04/2024-08:00 am	20.9	23/05/2024-08:00 am	20.3
23/04/2024-08:00 pm	20.9	23/05/2024-08:00 pm	20.4
24/04/2024-08:00 am	20.9	24/05/2024-08:00 am	20.3
24/04/2024-08:00 pm	20.9	24/05/2024-08:00 pm	20.3
25/04/2024-08:00 am	20.9	25/05/2024-08:00 am	20.2
25/04/2024-08:00 pm	20.8	25/05/2024-08:00 pm	20.3
26/04/2024-08:00 am	20.8	26/05/2024-08:00 am	20.3
26/04/2024-08:00 pm	20.8	26/05/2024-08:00 pm	20.3
27/04/2024-08:00 am	20.8	27/05/2024-08:00 am	20.3
27/04/2024-08:00 pm	20.8	27/05/2024-08:00 pm	20.2
28/04/2024-08:00 am	20.8	28/05/2024-08:00 am	20.2
28/04/2024-08:00 pm	20.8	28/05/2024-08:00 pm	20.2
29/04/2024-08:00 am	20.8	29/05/2024-08:00 am	20.2
29/04/2024-08:00 pm	20.8	29/05/2024-08:00 pm	20.2
30/04/2024-08:00 am	20.7	30/05/2024-08:00 am	20.2
30/04/2024-08:00 pm	20.8	30/05/2024-08:00 pm	20.2
		31/05/2024-08:00 am	20.2

		31/05/2024-08:00 pm	20.2
01/06/2024-08:00 am	20.2	16/06/2024-08:00 am	19.9
01/06/2024-08:00 pm	20.2	16/06/2024-08:00 pm	19.9
02/06/2024-08:00 am	20.1	17/06/2024-08:00 am	19.9
02/06/2024-08:00 pm	20.1	17/06/2024-08:00 pm	19.9
03/06/2024-08:00 am	20.1	18/06/2024-08:00 am	19.9
03/06/2024-08:00 pm	20.1	18/06/2024-08:00 pm	19.9
04/06/2024-08:00 am	20.1	19/06/2024-08:00 am	19.9
04/06/2024-08:00 pm	20.1	19/06/2024-08:00 pm	19.9
05/06/2024-08:00 am	20.1	20/06/2024-08:00 am	19.9
05/06/2024-08:00 pm	20.1	20/06/2024-08:00 pm	19.9
06/06/2024-08:00 am	20.1	21/06/2024-08:00 am	19.9
06/06/2024-08:00 pm	20.1	21/06/2024-08:00 pm	19.9
07/06/2024-08:00 am	20.1	22/06/2024-08:00 am	19.9
07/06/2024-08:00 pm	20.1	22/06/2024-08:00 pm	19.9
08/06/2024-08:00 am	20	23/06/2024-08:00 am	19.9
08/06/2024-08:00 pm	20	23/06/2024-08:00 pm	19.9
09/06/2024-08:00 am	20	24/06/2024-08:00 am	19.9
09/06/2024-08:00 pm	20	24/06/2024-08:00 pm	19.8
10/06/2024-08:00 am	20	25/06/2024-08:00 am	19.8
10/06/2024-08:00 pm	20	25/06/2024-08:00 pm	19.8
11/06/2024-08:00 am	20	26/06/2024-08:00 am	19.8

11/06/2024-08:00 pm	20	26/06/2024-08:00 pm	19.8
12/06/2024-08:00 am	20	27/06/2024-08:00 am	19.8
12/06/2024-08:00 pm	20	27/06/2024-08:00 pm	19.8
13/06/2024-08:00 am	20	28/06/2024-08:00 am	19.8
13/06/2024-08:00 pm	20	28/06/2024-08:00 pm	19.8
14/06/2024-08:00 am	19.9	29/06/2024-08:00 am	19.8
14/06/2024-08:00 pm	19.9	29/06/2024-08:00 pm	19.8
15/06/2024-08:00 am	19.9	30/06/2024-08:00 am	19.8
15/06/2024-08:00 pm	19.9	30/06/2024-08:00 pm	19.8

The aquifers of the study area can be broadly classified as:

Shallow aquifer: The shallow aquifer is composed of alluvium (loose sand) of recent deposit and soft, porous and loosely cemented sandstone and gritty sandstone of Kamthi Formation. The entire Bhanegaon OCM area is capped by Black cotton soil.

Below the soil cover, alluvial deposits composed of unconsolidated loose sand, pebbles and boulders whereas the underlying Kamthi Formation is represented by yellowish brown and porous medium to coarse grained ferruginous sandstone, gritty sandstone, shale and clay. Kamthis have overlapping nature and occur as blanket cover over the Barakars/Moturs unconformably. Because of their porous and coarse and gritty naure, the Kamthis are known to be highly potential aquifer. The contact between alluvial deposit and Kamthi Formation has not been well established as the core recovery is very poor in both the formations during the drilling the exploratory borehole. Therefore, Kamthi Formation together with alluvial deposit (loose sand) has been considered as Shallow Aquifer. Most of the dug wells in the area tap this aquifer by local people for their domestic and irrigation purposes. The Kamthi Formation on the other hand receives direct recharge from precipitation and in turn recharges the underlying Barakar Formation through vertical leakage.

Deep aquifer: The deeper aquifer is represented mainly by the Barakar Formation. The contact between Kamthi Formation and underlying Barakar/Motur Formation is unconformable in nature and represent the angular unconformity. The Barakar Formation is composed of fine to medium grained relatively compact sandstones, clay and shale with coal seams. The Barakar sandstone is hard, compact and cemented in compare to Kamthi sandstone and represents low to moderate potential aquifer. The vertical permeability of this aquifer is very less due to occurrence of impermeable coal seams/shale repeatedly.

3.1.3 MINING SYSTEM

Traditionally two methods of mining are available to extract the reserves by opencast mining:

a) Inclined Slicing Method

b) Horizontal Slicing Method

Considering multi seams and steep gradient of seams which falls in the range of 1 in 4.5 to 1 in 6, Horizontal Slicing Method is has been adopted for Bhanegaon OCM. The Excavation of Seam-V, IV Top, IV-Middle, IV-Bottom, III, II-Top & II-Bottom are being done by open cast method. The coal is exposed by removing O.B. in systematic way forming benches of prescribed height and width suitable for deployment of HEMM as mentioned in Table 3-1. Benches of soft soil/sand is stabilized by appropriate technique.

Figure 3.2 Bhanegaon OCM Benches

The proposed rated output of mine is 1.00 Mty of ROM Coal with the minable reserves of 24.00 Mt. The total life of the proposed opencast mine is estimated as 26 years including pre-construction period. Over all slope angle during working is 27^0 & Overall slope angle of non-working is 41^0.

Table 3.4 Bench Geometry

Types of material	Max. Height (m)	Max. Slope angle (^{O})	Bench Width (m)	Overall Slope Angle (in benches) (^{O})
Soil/Alluvium	3	60	9	34
Clayey soil	3	60	9	34
Coal	10	70	10	41
Rock Mass	10	70	20	41

3.2 LABORATORY INVESTIGATIONS

In laboratory Density, Porosity, Poisson's Ratio, Young's Modulus (MPa), Peak Tensile Strength (MPa), Friction Angle (Degrees), Cohesion (MPa) & Unconfined Compressive Strength were analysed by Stress-Strain analysis (IS 9221), Brazilian Tensile test (IS 10082), Triaxial test (IS 13047), Porosity test (IS 13030) & Unit weight (IS 13030).

Coal, Shale & Fine-grain, Medium-grain & Coarse-grain sandstone (from coal seam parting) were collected from mine site to determine physio-mechanical properties. NX size cores were cut with Diamond core cutting machine (Figure 3.3 & Figure 3.4) & then dried in oven so their properties can be determined in the lab as per tests mentioned above.

Figure 3.3 NX Size Core Cutting

Figure 3.4 Cores

Unit Weight: Unit weight (γ) of a rock is defined as its **weight per unit volume** and is critical for geotechnical analyses such as slope stability, foundation design, and rock mechanics. It is expressed as

$$\gamma = \frac{W}{V}$$

Where W= weight of the rock, and V= volume of the rock.

To determine unit weight of materials, diameter, length & mass of core samples of each material were measured and tests were performed in lab as per method prescribed in IS 13030. The unit weight for each material is given in below Tables:

Table 3.5 Unit Weight of Coarse-grain Sandstone

Samples	A	B	C	Average	Unit Weight (MN/M^3)
Diameter (mm)	52.6	52.7	50.3	52.225	0.018
Length (mm)	112.1	71.4	79.2	84.475	
Mass (gm)	448	280	280	330.75	

Table 3.6 Unit Weight of Medium-graine Sandstone

Samples	A	B	C	Average	Unit Weight (MN/M^3)
Diameter (mm)	53.7	53.7	53.5	53.633	0.020
Length (mm)	110.9	109.3	111.1	110.433	
Mass (gm)	502	511	498	503.667	

Table 3.7 Unit Weight of Fine-graine Sandstone

Samples	A	B	C	Average	Unit Weight (MN/M^3)
Diameter (mm)	54.1	54.5	54.1	54.233	0.021
Length (mm)	109.6	109.2	108.1	108.966	
Mass (gm)	538	539	517	531.333	

Table 3.8 Unit Weight of Shale

Samples	A	B	C	Average	Unit Weight (MN/M^3)
Diameter (mm)	53.9	54.7	54.7	54.433	0.020
Length (mm)	109	112.1	110.5	110.533	
Mass (gm)	517	539	527	527.667	

Table 3.9 Unit Weight of Coal

Samples	A	B	C	Average	Unit Weight (MN/M^3)
Diameter (mm)	54.8	54.9	54.7	54.8	0.015
Length (mm)	103.9	109.4	109.1	107.4667	
Mass (gm)	357	381	382	373.3333	

Porosity: Porosity is the ratio of the volume of voids to the total volume of the rock specimen, usually expressed as a percentage. It indicates the storage capacity of rocks for fluids like water, oil, or gas.

$$\textbf{Porosity } (\boldsymbol{\phi}) = \left(\frac{\mathbf{Vv}}{\mathbf{Vt}}\right) \times \mathbf{100}$$

Where:

Vv = Volume of voids Vt = Total volume of rock specimen

Porosity of rock samples was calculated as per procedure prescribed in IS 13030 standard. Weight of dry, saturated & submerged specimen were taken and porosity was calculated (Table 3.10)

Volume and Porosity Calculation (IS 13030):

Volume of specimen (V): $V=Ws-Wsub$

Volume of voids (Vv): $Vv=Ws-Wd$

Where: Ws = Saturated Weight of Specimen, Wsub = Submerged Weight of Specimen

Wd = dry Weight of Specimen

(Assuming unit weight of water = 1 g/cm^3)

Porosity (ϕ):

$$\boldsymbol{\phi = \frac{(Ws - Wd)}{Ws - Wsub} \times 100}$$

Table 3.10 Porosity of Rock Specimens

	Dry Weight (gm)	Saturated Weight (gm)	Submerged Weight (gm)	Porosity
Coarse-grain Sandstone	35.305	38.7	16.067	0.150
Medium-grain Sandstone	59.086	63.787	34.406	0.160
Fine-grain Sandstone	44.641	48.226	24.326	0.150
Shale	59.663	63.781	33.723	0.137
Coal	16.378	17.435	5.000	0.085

Peak Tensile Strength: The Brazilian Tensile Test is an indirect method to determine the tensile strength of rocks, as per the Indian Standard IS 10082:1981. It is widely used due to its simplicity and applicability to brittle materials.

A cylindrical rock disc is subjected to diametral compressive loading until failure. The induced tensile stress at the center of the disc causes splitting along the diameter, allowing calculation of tensile strength.

Tensile Strength (σ_t) (MPa) is calculated using:

$$\sigma_t = \frac{2P_{\max}}{\pi D t}$$

where:

P_{max}=Maximum load (N)

D=Specimen diameter (mm)

t=Specimen thickness (mm)

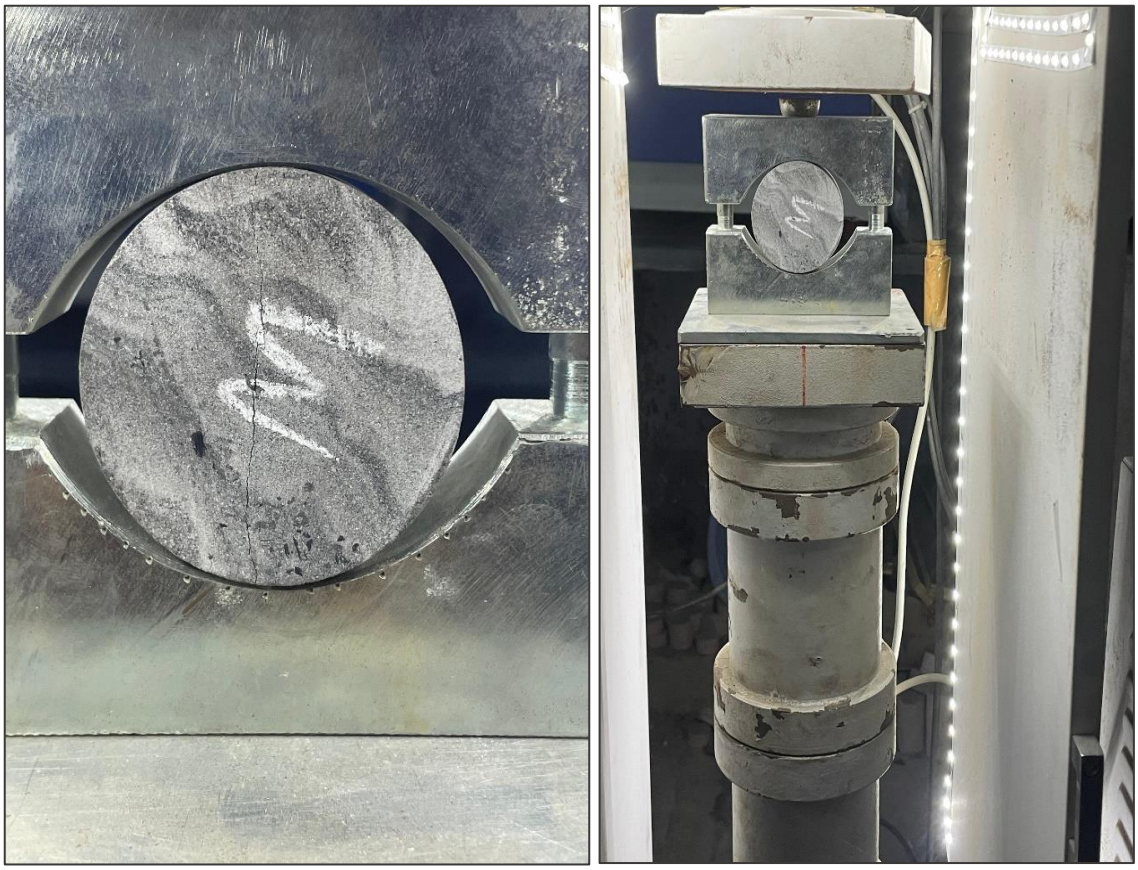

Figure 3.5 Brazilian Testing

Figure 3.6 Rock Specimens after Brazilian Testing

The Brazilian Tensile Test was performed as per the Indian Standard IS 10082:1981 (Figure 3.5 & Figure 3.6) & obtained results are:

Table 3.11 Peak tensile Strength of Coarse-grain Sandstone

Samples	A	B	C	Average Peak Tensile Strength (MPa)
Diameter (mm)	54	53	51.12	0.384
Length (mm)	31.03	32.24	30.87	
Mass (gm)	125	127	116	
Maximum Load (KN)	1.12	0.5	0.68	
Tensile Strength (MPa)	0.425	0.186	0.274	

Table 3.12 Peak tensile Strength of Medium-grain Sandstone

Samples	A	B	C	Average Peak Tensile Strength (MPa)
Diameter (mm)	53.91	54.09	54.7	0.785
Length (mm)	27.48	27.05	28.01	
Mass (gm)	121	125	130	
Maximum Load (KN)	1.26	1.86	2.42	
Tensile Strength (MPa)	0.541	0.809	1.00	

Table 3.13 Peak tensile Strength of Fine-grain Sandstone

Samples	A	B	C	Average Peak Tensile Strength (MPa)
Diameter (mm)	54.14	54.22	54.77	1.137
Length (mm)	24.61	27.87	31.17	
Mass (gm)	115	127	150	
Maximum Load (KN)	2.54	2.4	3.18	
Tensile Strength (MPa)	1.213	1.011	1.185	

Table 3.14 Peak tensile Strength of Shale

Samples	A	B	C	Average Peak Tensile Strength (MPa)
Diameter (mm)	54.83	54.96	54.75	1.800
Length (mm)	29.91	27.07	27.84	
Mass (gm)	101	86	91	
Maximum Load (KN)	3.46	4.48	5.38	
Tensile Strength (MPa)	1.343	1.917	2.247	

Table 3.15 Peak tensile Strength of Coal

Samples	A	B	C	Average Peak Tensile Strength (MPa)
Diameter (mm)	54.7	55.56	55.6	2.290
Length (mm)	25.89	27.64	31.03	
Mass (gm)	118	118	144	
Maximum Load (KN)	5.48	5.6	5.62	
Tensile Strength (MPa)	2.463	2.321	2.073	

Poisson's ratio: Poisson's ratio (ν) is a dimensionless material property that quantifies the ratio of transverse strain to axial strain under uniaxial loading. It describes how a rock deforms laterally when compressed or stretched axially. For most rocks, Poisson's ratio ranges between 0.1 and 0.4, depending on lithology, porosity, and stress conditions.

$$\nu = -\frac{\epsilon_{\text{transverse}}}{\epsilon_{\text{axial}}}$$

where: $\epsilon_{\text{transverse}}$ = Strain perpendicular to the applied load

ϵ_{axial} = Strain parallel to the applied load.

Young's Modulus: Young's modulus (E) is a measure of a rock's stiffness or resistance to elastic deformation under stress. It is defined as the ratio of axial stress (σ) to axial strain (ϵ)in the linear elastic region of a stress-strain curve:

$$E = \frac{\sigma}{\epsilon}$$

Young's modulus is critical for predicting rock behavior in engineering applications such as tunneling, mining, and hydraulic fracturing.

Young's modulus & Poisson's ratio were determined by stress-strain analysis as per Indian Standard IS 9221.

Figure 3.7 Rock Specimens after Stress-Strain analysis & Dial Gauge with LC 0.01mm

Table 3.16 Specimen-1 Coarse-grain Sandstone

Load (Kg)	L1	L2	L3
0	0	0	0
200	10	0	2
400	53	-2	19
600	86	0	25
800	125	8	23

Where: L1 Change in Length in Longitudinal Direction

L2 & L3 Change in Diameter in Lateral Direction

Table 3.17 Specimen-2 Coarse-grain Sandstone

Load (Kg)	L1	L2	L3
0	0	0	0
200	33	-9	6
400	76	-50	82

Poisson's ratio & Young's Modules (MPa) of **Coarse-grain Sandstone** is based on calculation from above laboratory data is 0.200 & 192.172 respectively.

Table 3.18 Specimen-1 Medium-grain Sandstone

Load (Kg)	L1	L2	L3
0	0	0	0
200	15	6	-4
400	40	13	-8
600	60	17	-11
800	76	19	-13
1000	90	20	-14

Table 3.19 Specimen-2 Medium-grain Sandstone

Load (Kg)	L1	L2	L3
0	0	0	0
200	7	-2	3
400	30	-10	9
600	45	-12	12
800	58	-13	15
1000	65	-14	17
1200	75	-14	19
1400	86	-14	22

Table 3.20 Specimen-3 Medium-grain Sandstone

Load (Kg)	L1	L2	L3
0	0	0	0
200	10	2	-2
400	43	6	-6
600	79	12	-12
800	104	20	-14
1000	120	24	-12
1200	135	26	-3

Poisson's ratio & Young's Modules (MPa) of **Medium-grain Sandstone** is based on calculation from above laboratory data is 0.165 & 474.860 respectively.

Table 3.21 Specimen-1 Fine-grain Sandstone

Load (Kg)	L1	L2	L3
0	0	0	0
200	7	0	1
400	47	1	4
600	52	4	4
800	67	9	4
1000	76	12	4
1200	85	15	3
1400	97	19	3
1600	105	22	3
1800	114	25	4
2000	127	29	7

Table 3.22 Specimen-2 Fine-grain Sandstone

Load (Kg)	L1	L2	L3
0	0	0	0
200	20	6	-3
400	61	17	-6

600	80	20	-7
800	88	20	-7
1000	95	21	-7
1200	105	22	-6
1400	112	22	-6
1600	120	23	-6
1800	130	23	-6
2000	139	23	-5
2200	161	17	10

Table 3.23 Specimen-3 Fine-grain Sandstone

Load (Kg)	L1	L2	L3
0	0	0	0
200	6	-2	4
400	23	-4	6
600	36	-7	9
800	46	-9	10
1000	52	-10	10
1200	59	-11	10
1400	67	-10	10
1600	76	-10	9
1800	88	-9	7
2000	101	-9	5

Poisson's ratio & Young's Modules (MPa) of **Fine-grain Sandstone** is based on calculation from above laboratory data is 0.186 & 1051.400 respectively.

Table 3.24 Specimen-1 Shale

Load (Kg)	L1	L2	L3
0	0	0	0
200	12	-4	5
400	50	-7	11
600	79	-1	5
800	99	2	4
1000	109	4	3
1200	126	8	-2
1400	152	19	-12
1600	180	27	-19
1800	195	30	-21
2000	209	30	-20

Table 3.25 Specimen-2 Shale

Load (Kg)	L1	L2	L3
0	0	0	0
200	11	-2	3
400	38	-4	7
600	66	-1	5
800	88	0	5
1000	101	1	4
1200	112	1	3
1400	124	2	2
1600	139	3	2
1800	149	4	1
2000	161	5	1
2200	173	5	1

Poisson's ratio & Young's Modules (MPa) of **Shale** is based on calculation from above laboratory data is 0.135 & 616.981 respectively.

Table 3.26 Specimen-1 Coal

Load (Kg)	L1	L2	L3
0	0	0	0
200	16	4	-3
400	61	3	-1
600	83	5	-1
800	105	10	-6
1000	114	10	-5
1200	122	10	-4
1400	131	11	-5
1600	140	11	-4
1800	149	11	-3
2000	166	10	-2
2200	165	10	-1
2400	173	10	0
2600	182	10	1
2800	188	10	2
3000	197	10	2
3200	200	-3	15
3400	240	-6	22

Table 3.27 Specimen-2 Coal

Load (Kg)	L1	L2	L3
0	0	0	0
200	11	2	-2
400	37	5	-6
600	51	6	-8
800	62	6	-8
1000	69	6	-9
1200	77	8	9
1400	85	7	-10

1600	91	7	-10
1800	97	8	-10
2000	103	8	-10
2200	110	8	-10
2400	117	9	-10
2600	125	10	-10
2800	132	10	-10
3000	139	10	-11
3200	145	11	-11
3400	153	12	-11
3600	160	12	-11
3800	166	13	-11
4000	175	13	-11
4200	182	14	-11

Poisson's ratio & Young's Modules (MPa) of **Coal** is based on calculation from above laboratory data is 0.055 & 1206.190 respectively.

Triaxial Test: The Triaxial Test is a standard laboratory test used to determine the shear strength parameters (cohesion and angle of internal friction) of soil and rock samples under controlled stress conditions. It is widely used in geotechnical engineering, including for assessing slope stability in opencast mines.

Cohesion (c) & angle of internal friction (φ) is calculated using mohr-columb failure criteria:

$$\tau = c + \sigma \tan\phi$$

where:

τ is shear strength

σ is normal stress.

Tri-axial test was performed in laboratory as per India Standard IS-13047 (Figure 3.8 & Figure 3.9). The corresponding results for each sample are shown in below tables.

Figure 3.8 Tri-axial testing of Rock Samples

Figure 3.9 Rock Samples after Tri-axial Testing

Table 3.28 Cohesion & Angle of Friction of Coarse-grain Sandstone

	Sample A	Sample B	Sample C	Cohesion (MPa)	Angle of Friction (º)
Confining Pressure (kg/cm^2)	25	50	75	8.424	38.900
Length (cm)	107.4	108.4	107.8		
Diameter (cm)	54.2	54.6	52.7		
Weight (gm)	494	508	481		
Axial Load at Failure (kg)	5000	8000	8500		

Table 3.29 Cohesion & Angle of Friction of Medium-grain Sandstone

	Sample A	Sample B	Sample C	Cohesion (MPa)	Angle of Friction (º)
Confining Pressure (kg/cm^2)	25	50	75	12.110	29.750
Length (cm)	109.3	109.2	111.4		
Diameter (cm)	54	53.3	54.3		
Weight (gm)	495	488	531		
Axial Load at Failure (kg)	5500	7500	9000		

Table 3.30 Cohesion & Angle of Friction of Fine-grain Sandstone

	Sample A	Sample B	Sample C	Cohesion (MPa)	Angle of Friction (º)
Confining Pressure (kg/cm^2)	25	50	75	29.300	38.718
Length (cm)	110	110	109		
Diameter (cm)	54.6	53.8	54.4		
Weight (gm)	533	522	516		
Axial Load at Failure (kg)	6000	8000	11000		

Table 3.31 Cohesion & Angle of Friction of Shale

	Sample A	Sample B	Sample C	Cohesion (MPa)	Angle of Friction (°)
Confining Pressure (kg/cm^2)	25	50	75	13.226	36.210
Length (cm)	94.5	111.3	110.9		
Diameter (cm)	54.3	54.6	54.3		
Weight (gm)	445	524	522		
Axial Load at Failure (kg)	7500	9000	12000		

Table 3.32 Cohesion & Angle of Friction of Coal

	Sample A	Sample B	Sample C	Cohesion (MPa)	Angle of Friction (°)
Confining Pressure (kg/cm^2)	25	50	75	18.663	30.030
Length (cm)	96.7	103.5	115.8		
Diameter (cm)	54.8	54.7	54.7		
Weight (gm)	328	356	381		
Axial Load at Failure (kg)	8000	10000	12500		

All test results obtained above are summarized in below Table 3.33. These Geo-mechanical properties were further used in numerical modelling in RS2.

Table 3.33 Geo-mechanical properties of rock

Material Properties	**Black Cotton** (Ghosh et al., 1990)	**Alluvial Soil** (Bansal et al., 2010)	**Coal**	**Shale**	**Coarse Grain Sandstone**	**Medium Grain Sandstone**	**Fine Grain Sandstone**
Unit Weight (MN/M^3)	0.015	0.018	0.015	0.020	0.018	0.020	0.021
Porosity Value	0.350	0.250	0.085	0.137	0.150	0.160	0.150
Poisson's Ratio	0.200	0.200	0.055	0.135	0.200	0.165	0.186
Young's Modulus (MPa)	10.000	20.000	1206.190	616.981	192.172	474.860	1051.400
Peak Tensile Strength (MPa)	0.050	0.100	2.290	1.800	0.384	0.785	1.137
Friction Angle (Degrees)	15.000	30.000	30.030	36.210	38.900	29.750	38.718
Cohesion (MPa)	0.050	0.020	18.663	13.326	8.424	12.110	29.300

4 NUMERICAL MODELLING

To determine mine profile Terrestrial Laser Scanner (TLS) was used and sections were created. Total 5 equidistance sections were created across the strike line to study the mine as these sections encompasses entire mining area (Figure 4.1). Sections are 550,750,950,1150 & 1350.

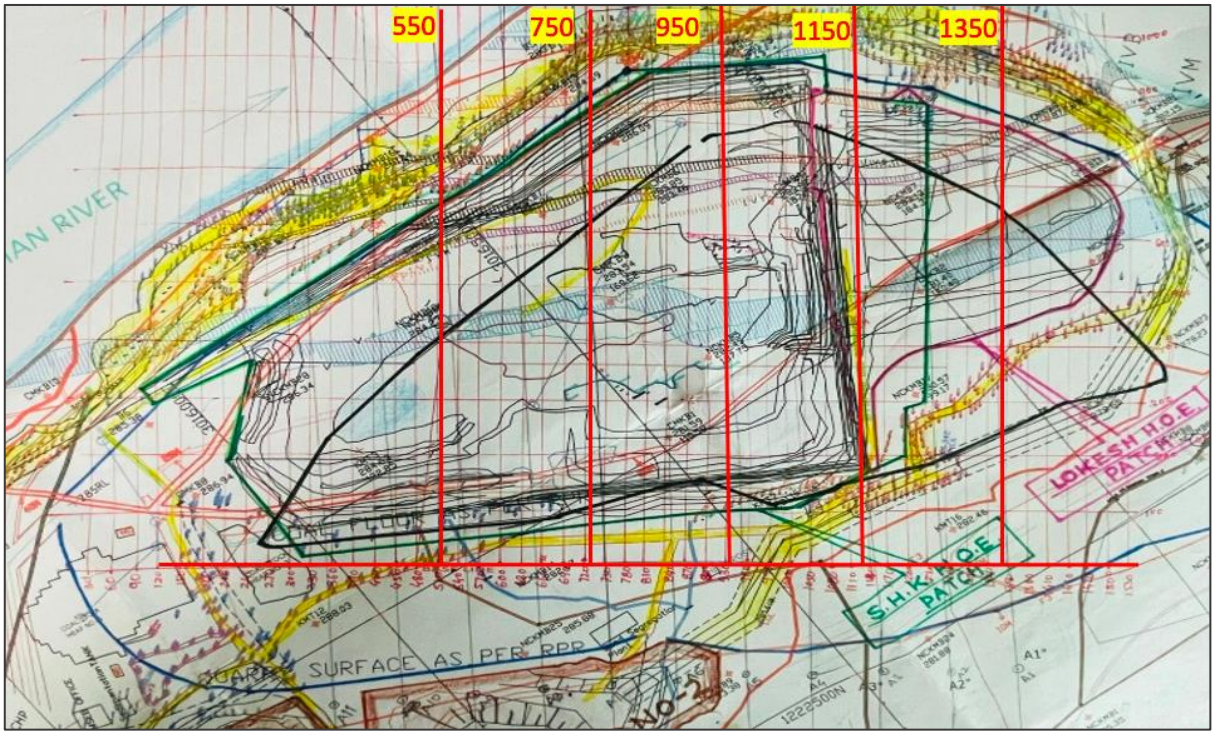

Figure 4.1 Mine Plan with Sections

4.1 Model Preparation

For slope stability analysis models were created using the computer program (RS2). For model creation, first outer boundary was created with respective section co-ordinates and subsequently material layers were created with their properties as mentioned in Table 3. 33. Details of different lithologies and their colour representation in models are shown in Table 4.1. Fault plane & Piezometric data were also used before Discretization & Meshing (Figure 4.11). The procedure of model preparation by RS2 is as follows:

1. Click on the “Boundary Menu” on the screen, select “Add External” as shown in Figure 4.2

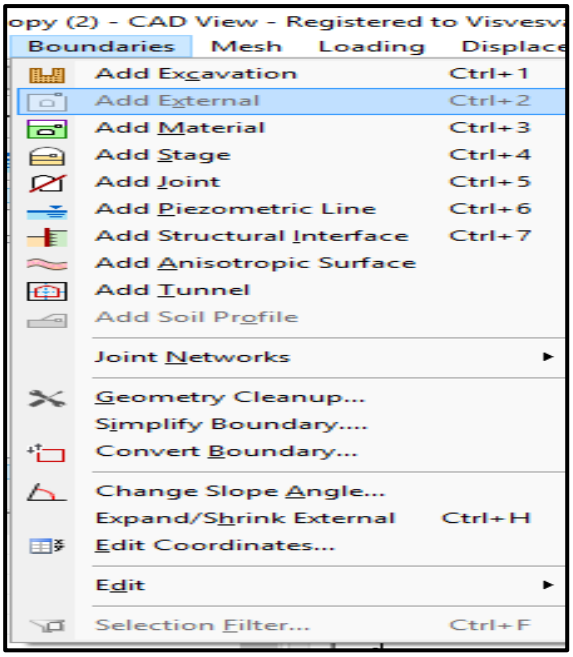

Figure 4.2 Boundary Menu of RS2

2. Enter the coordinates at the right bottom rectangular box in (X, Y) format as shown in the Figure 4.3 & outline of section will be created.

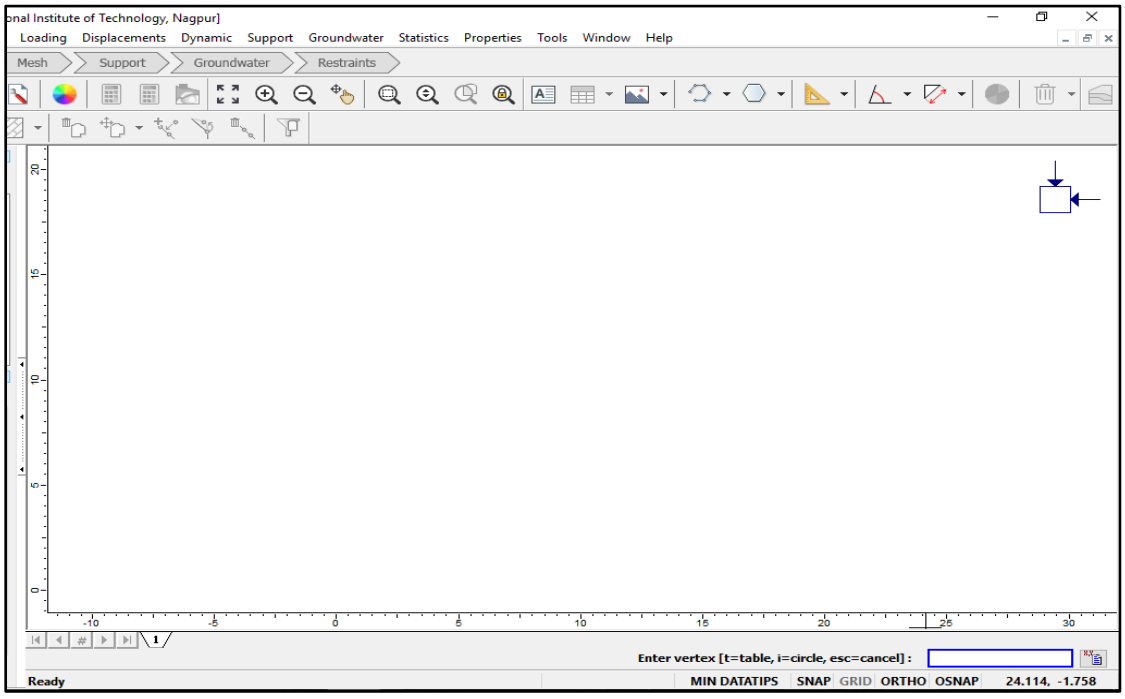
Loading Displacements Dynamic Support Groundwater Statistics Properties Tools Window Help
Mesh Support Groundwater Restraints
Enter vertex [t=table, i=circle, esc=cancel] :
Ready
MIN DATATIPS SNAP GRID ORTHO OSNAP 24.114, -1.758

Figure 4.3 Coordinate Input Menu

To get the coordinate of particular section (Figure 4.4), file obtained from TLS is opened in Autocad & command "List" is given in command prompt.

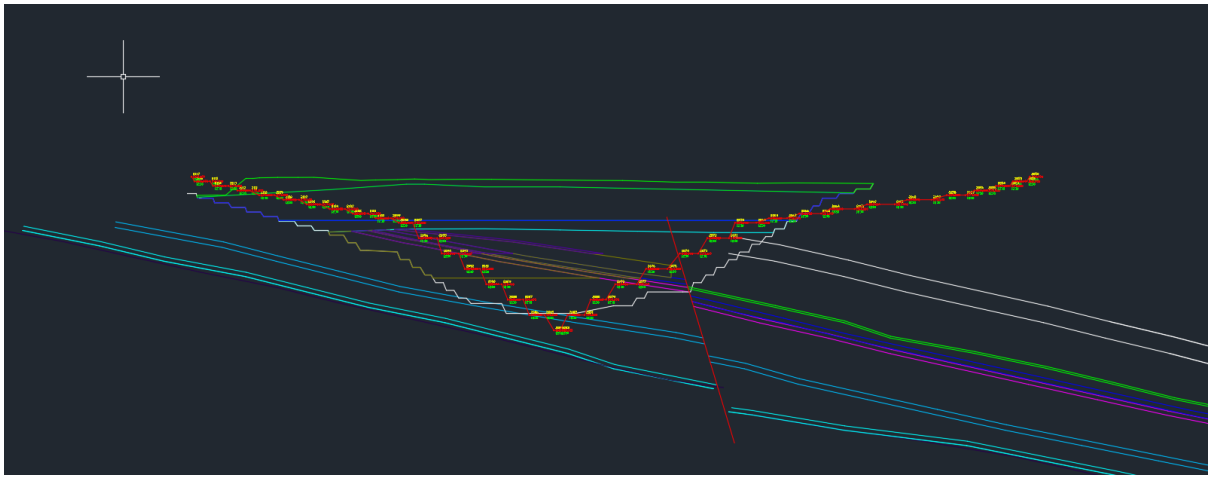

Figure 4.4 Mine Section obtained from TLS

3. After Geometry has been formed, the layers has to be added. The layers are added by clicking “Boundaries” Menu as shown in Figure 4.5. Then, click on “Add Materials”

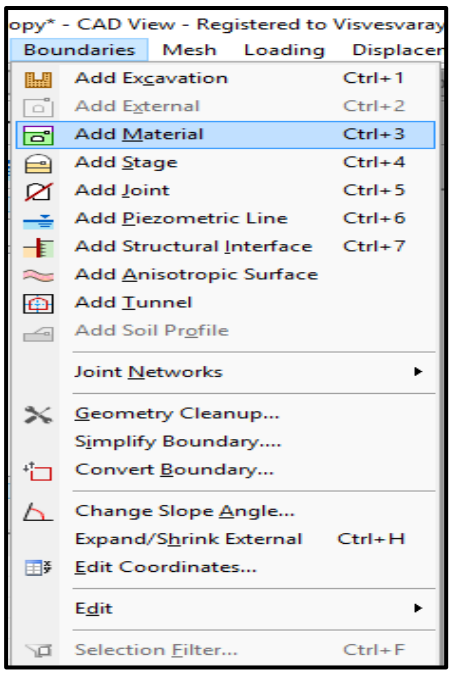

Figure 4.5 Boundary Menu to Add Layers

4. Right click on the region forms after adding the layers, click on “Assign Material” then add layers one by one as shown in Figure 4.6.

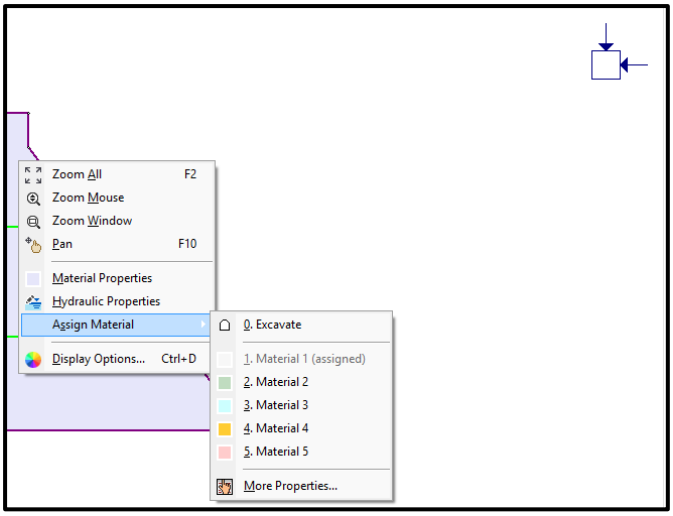

Figure 4.6 Assigning Material to Layers

5. Assign properties to the layer added, by right clicking anywhere in the section which properties have to been assigned and then click on the "Material Properties" as shown in Figure 4.7.

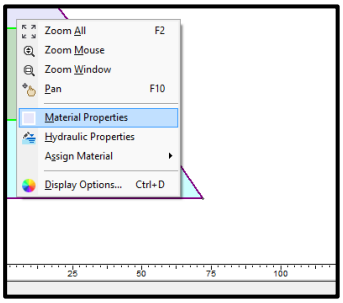

Figure 4.7 Options for Assigning Material Properties

Assigned materials & their colour representation is shown in Table 4.2 and created section-1350 is shown in Figure 4.8. Properties are assigned to all materials from Table 3.33, which were obtained after lab testing including water table& fault.

Table 4.1 Material & their color representation in model

Material Name	Black Cotton	Alluvial Soil	Coal	Shale	Medium Grain Sandstone	Coarse Grain Sandstone	Fine Grain Sandstone
Material Color							

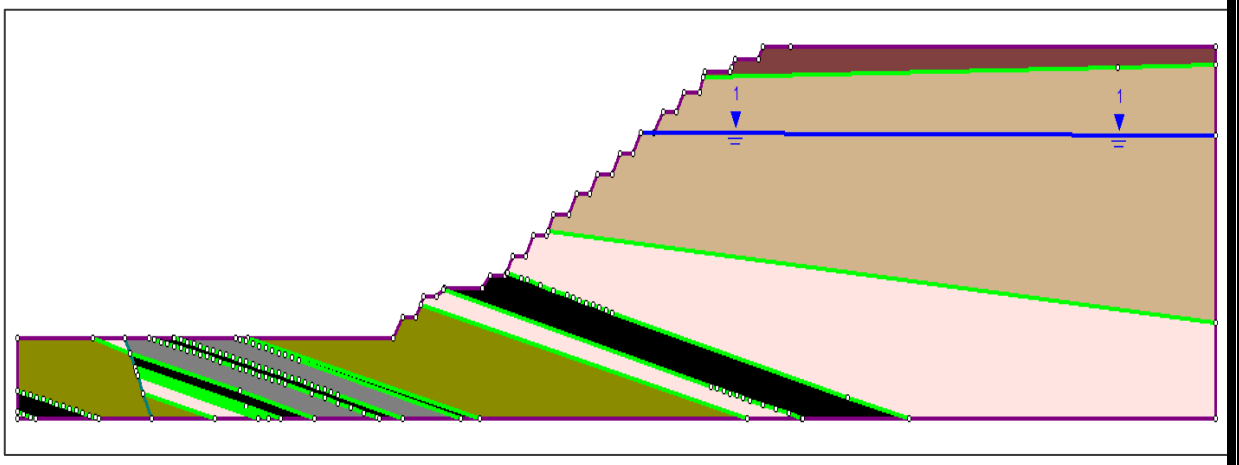

Figure 4.8 Mine Section (1350) Geometry with Material Layers, Water Table & Fault

6. After this apply the mesh to the geometry as shown in the Figure 4.9. Click on "Mesh Setup" dialogue box will appear as shown in the Figure 4.10. Click on "Discretise" then "Mesh".

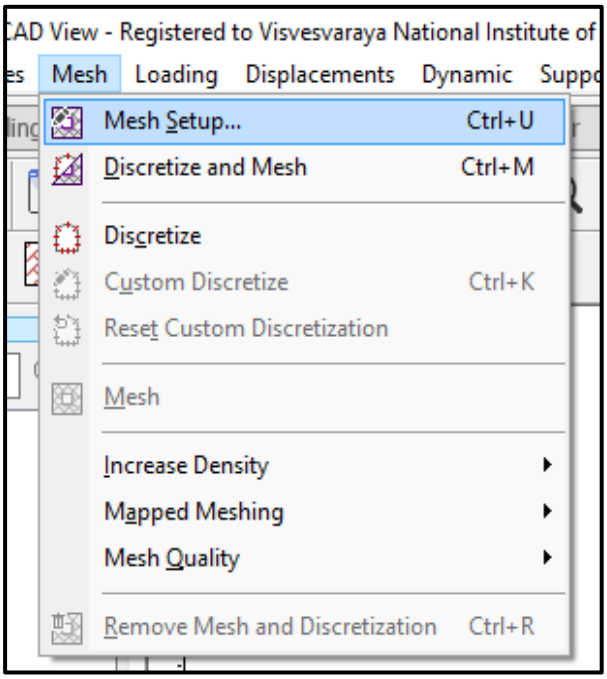

Figure 4.9 Mesh Setup

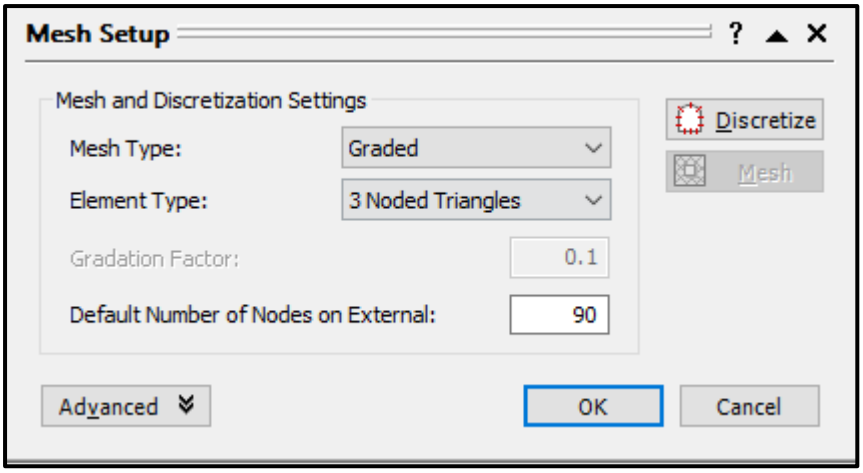

Figure 4.10 Mesh Setting

7. Click on "Displacement" menu, click on "Free", click on benching side of section and click on "Apply". Section-1350 after discretization & applying the displacement is shown in the Figure 4.11.

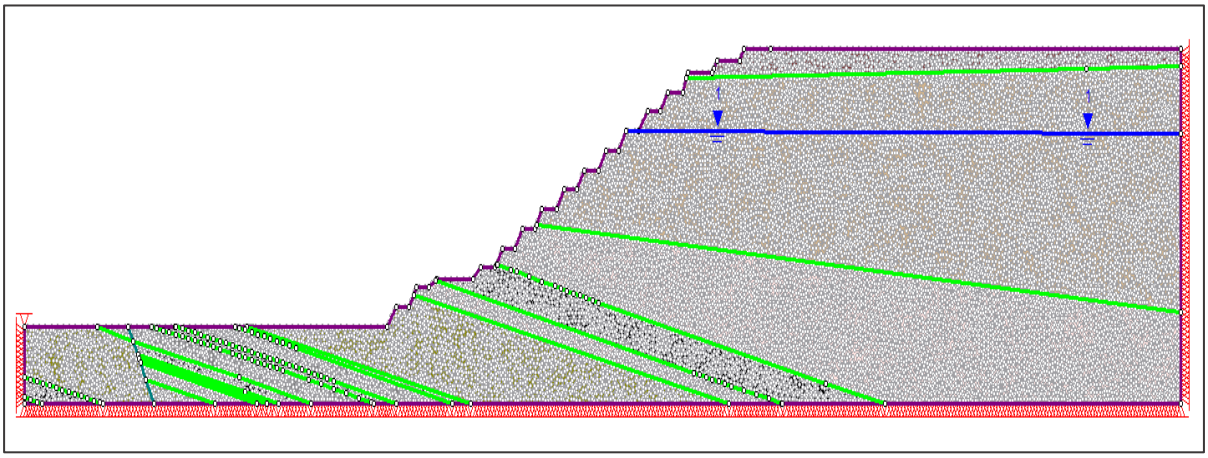

Figure 4.11 Final Section-1350 Geometry

8. Click on compute button, at the top menu bar then click on "OK". After that model is saved at the particular destination shown in Figure 4.12.

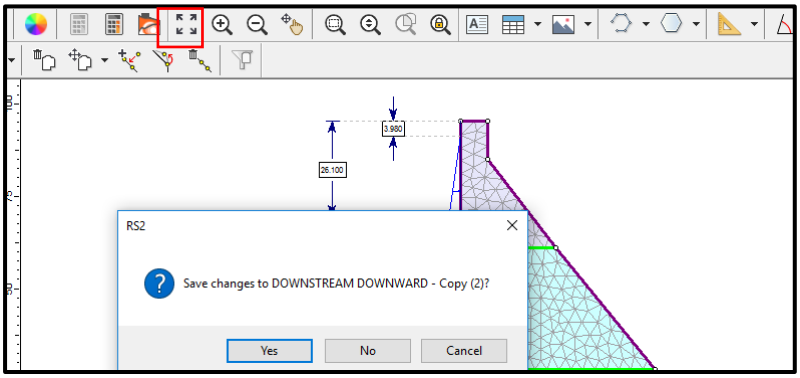

Figure 4.12 Model Computation

9. Click on interpret symbol, the model will get interpreted and results are recorded in terms of stress and displacement, which will be discussed in next section. With above-described procedure all remaining sections are created.

5 RESULT & DISCUSSION

Stability of a mine section depends on a variety of factors including SRF, maximum displacement and maximum stress. A high SRF (>1) means that the structure is more resistant to failure, while a low SRF signals higher risk for collapse or movement.

Maximum displacement helps identify areas where the mine section may be deforming excessively, signalling potential risks for instability. Monitoring and understanding the stress distribution is essential to prevent failure due to overstressed sections and to ensure that excavation activities do not introduce risks to stability.

A low SRF combined with high displacement and high stress suggests that the mine section is at a high risk of instability. Conversely, a high SRF, low displacement and moderate stress would indicate a more stable condition.

The prepared models were analysed with maximum SRF tolerance 0.01 for precision in result. A small tolerance (0.01) would ensure more accurate Factor of Safety (FOS) by fine tuning the SRF value before failure occurs. After computation Critical SRF was determined with maximum displacement. At present mining operations are going smoothly without any safety disturbances as per DGMS guideline in soft material (106(4) of Coal Mines Regulations, 2017).

After interpretation of models in RS2, results are recorded in terms of stress and displacement. Critical SRF obtained through RS2 modelling of sections 550, 750, 950, 1150 & 1350 are 1.95, 1.53, 2.09, 1.37 & 1.18 respectively, which showing the safe working conditions (Figure 5.1 to 5.5).

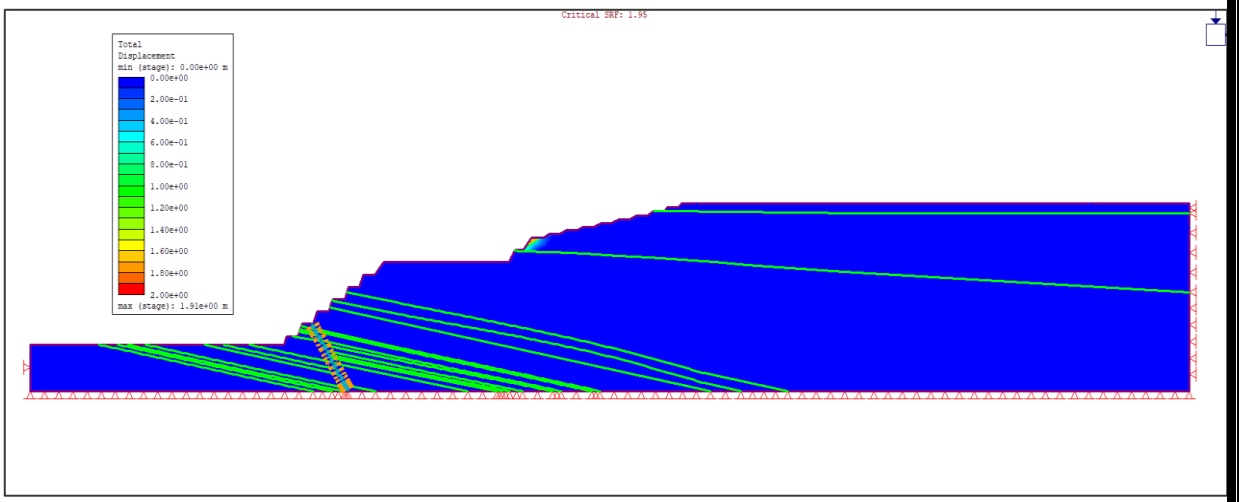

Figure 5.1 Critical SRF of Section 550

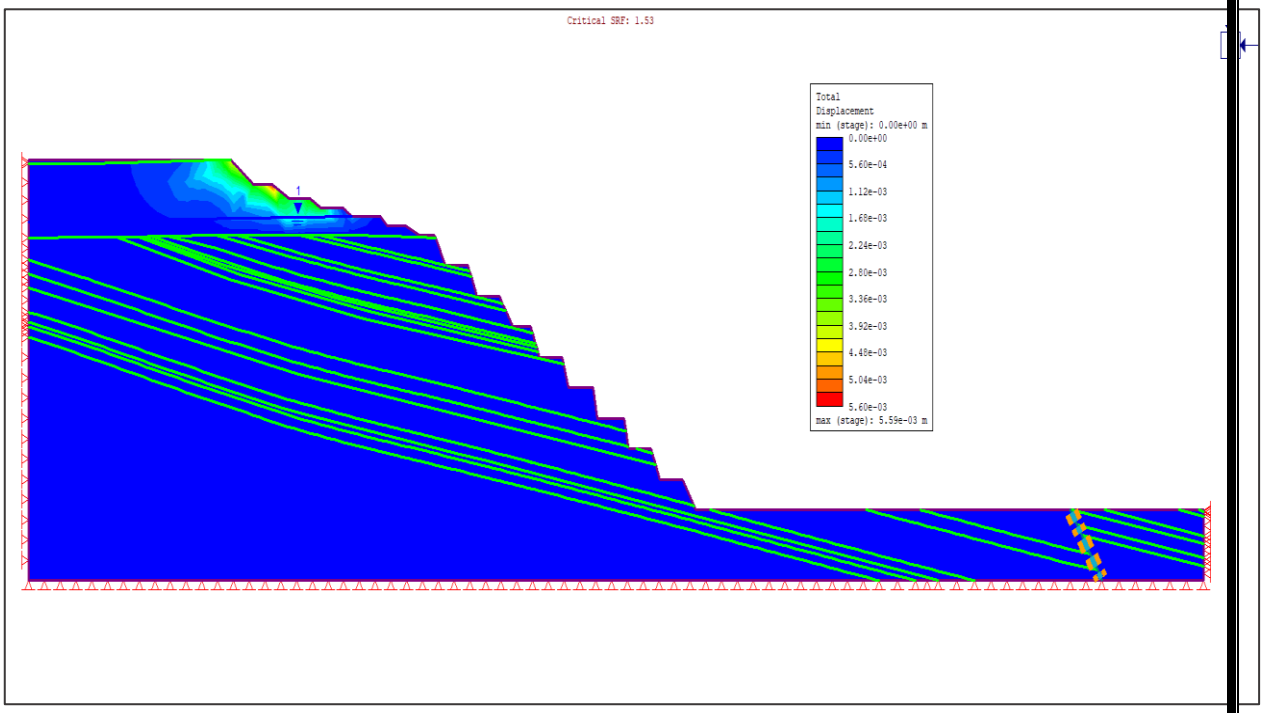

Figure 5.2 Critical SRF of Section 750

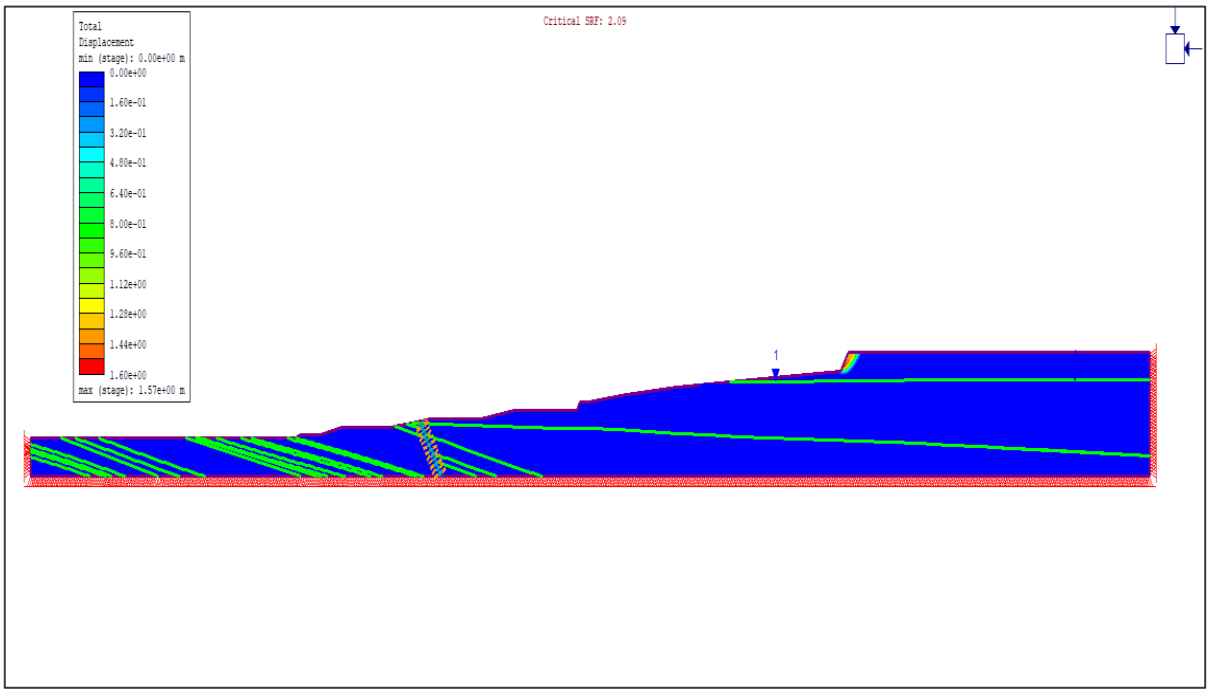

Figure 5.3 Critical SRF of Section 950

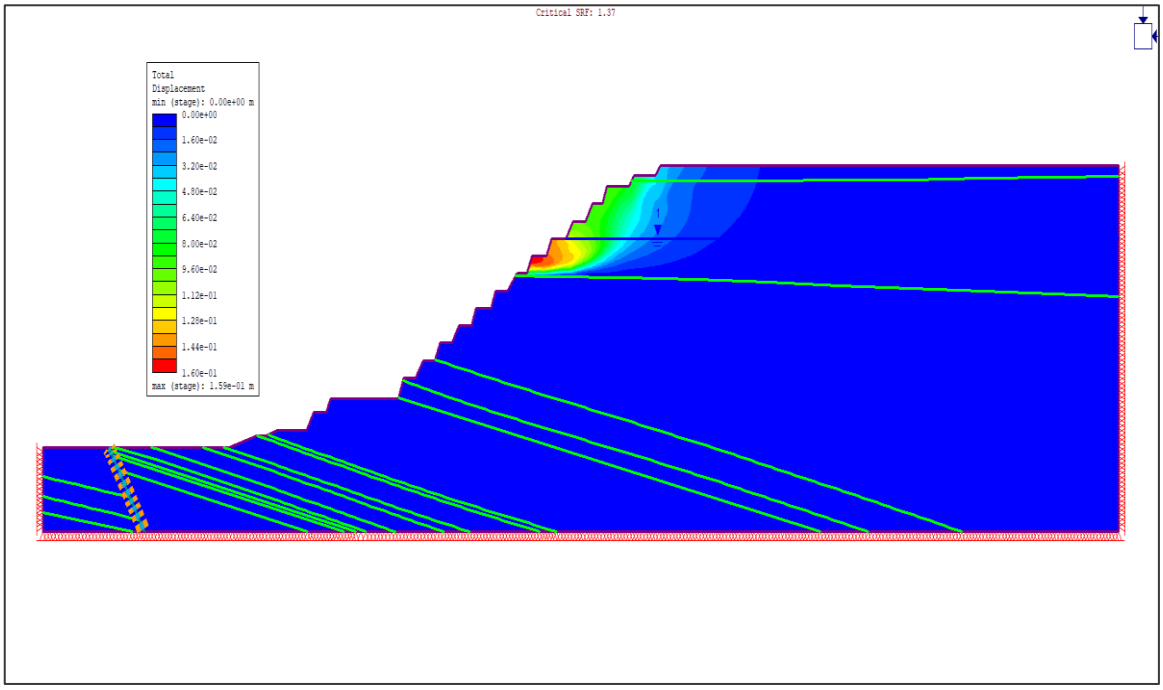

Figure 5.4 Critical SRF of Section 1150

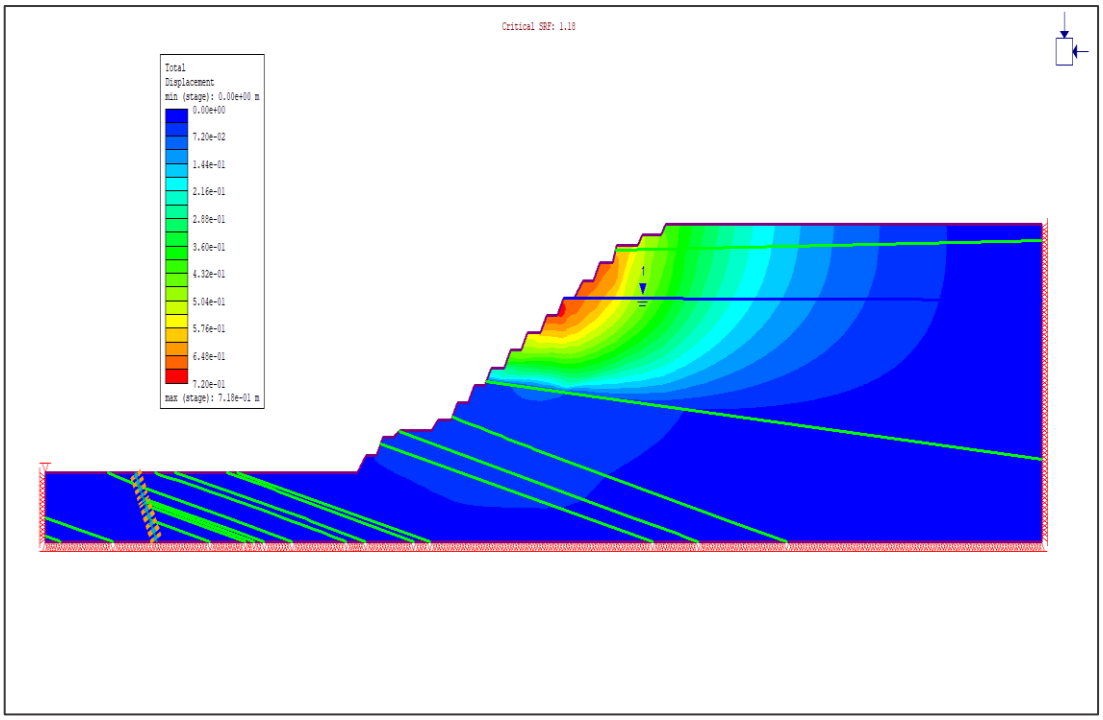

Figure 5.5 Critical SRF of Section 1350

In this analysis, all the sections were stable with more than one critical SRF (Figure 5.6). Further, the prepared sections were analysed based on their horizontal movement (displacement) and stress generated. Max. displacement (meter) & max. stress (MPa) of sections 550, 750, 950, 1150, & 1350 are 1.900 & 87.38, 0.005 & 2.52, 1.570 & 1.33, 0.158 & 1.99, 0.718 & 1.83 respectively as shown in Figure 5.7 & Figure 5.8.

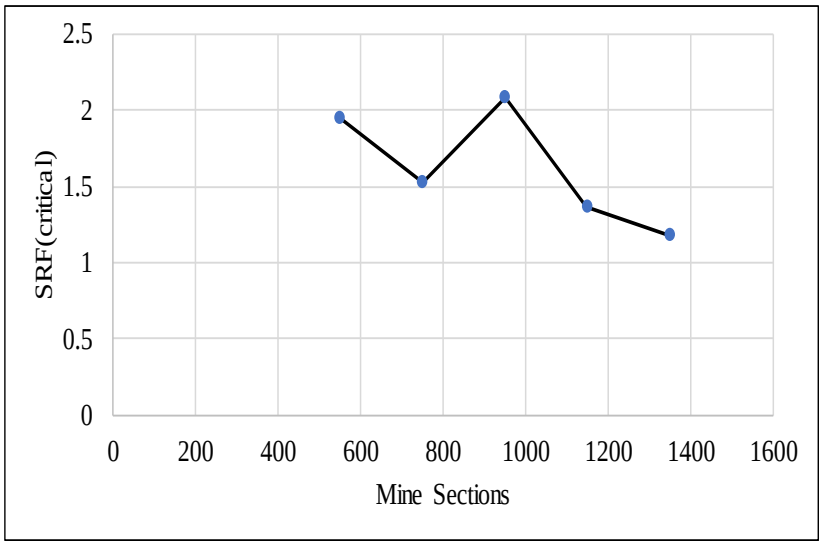

Figure 5.6 Critical SRF of all Sections

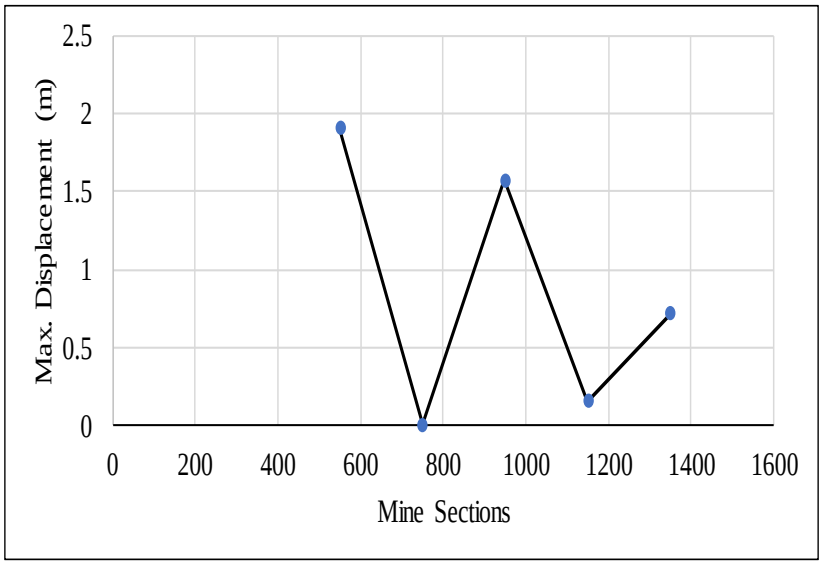

Figure 5.7 Maximum Displacement of all Sections

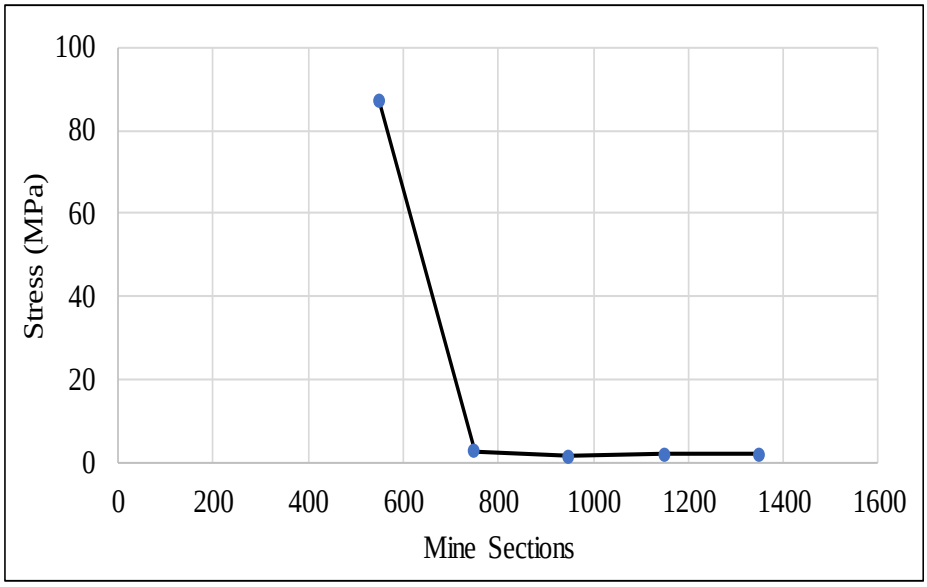

Figure 5.8 Maximum Stress of all Sections

The numerical RS2 analysis yielded critical Stress Reduction Factors (SRFs) for each cross-section that indicate overall stability. All five sections (550, 750, 950, 1150, 1350) exhibited SRF > 1, implying global factor-of-safety conditions. By convention, higher SRF values denote more robust slopes, whereas values near unity signal marginal stability. Here, Section 950 and Section 550 show the highest SRFs (≈2.09 and 1.95 respectively) & in contrast, Section 1350 has the lowest SRF (~1.18), barely above unity, which approaches the lower threshold of SRF. Overall, these SRF results indicate that, under static conditions and current bench design, all analyzed slopes are nominally stable (SRF >1).

The computed maximum displacements and stresses for each section varied markedly. Section 550 recorded a very large lateral movement (~1.900 m) and extremely high stress (~87.4 MPa), far exceeding the other sections. Section 950 also showed substantial displacement (~1.570 m) but with relatively low peak stress (~1.33 MPa). By comparison, Sections 750, 1150, and 1350 had much smaller deformations: 0.005 m, 0.158 m, and 0.718 m, respectively. Their peak stresses were on the order of 1–2 MPa. In summary, Section 550 is an outlier in both metrics (high movement and stress), Section 950 has high movement but low stress, and the others exhibit low movement (especially 750) and low stress. This suggests that Section 750 and 1150 are relatively rigid profiles, whereas 550 and 950 contain more deformable or weak layers. Such variations highlight that factor-of-

safety alone does not capture the magnitude of deformations; even a slope with adequate FS may show significant strain if material stiffness is low. Section 550 deserves special attention. Despite its healthy SRF of ~1.95, it experiences by far the greatest displacement (~1.9 m) and stress concentration (~87 MPa). This apparent paradox arises from local ground conditions. Section 550 is located in the SW portion of the mine where a thick, water saturated alluvial cover overlies the Kamthi formation. The alluvium, which contains black cotton and sand bands, has very low cohesion; numerical analysis showed that sections with such sand–clay layers have markedly lower SRF due to reduced shear strength. In Section 550 these weak, high-transmissivity layers permit large deformation under gravity, producing high displacement and stress even though the global SRF remains >1. In practice, this means that Section 550, while formally "stable," is deforming significantly- a red flag for potential failure if conditions change. In other words, the global FS criterion is satisfied, but local distortion is severe enough to warrant caution.

The geological setting strongly influences these results. As discussed earlier the entire Bhanegaon block is blanketed by 20– 57 m of alluvial deposits (black cotton soils, riverine sand and sludge) over the Gondwana Kamthi formation. The alluvium's poor strength and high-water content (high transmissivity) greatly reduce slope stability. As noted in the study, sections containing such sand/clay bands had significantly lower SRF because the upper weak layers lose cohesion when saturated. The black cotton soils are known to swell and weaken when wet, further undermining bench stability. Thus, the combination of thick, water-bearing alluvium and the heterogeneous Kamthi sandstone (often with clayey partings) leads to the observed lower safety margins and larger deformations in certain sections.

6 CONCLUSION

This study evaluated the slope stability of Bhanegaon Opencast Coal Mine, located at the confluence of the Pench and Kanhan Rivers, where complex geological conditions—including loose, saturated alluvial cover and high-transmissivity Kamthi formations—pose potential threats to safe mining operations. Through comprehensive field and laboratory investigations, followed by advanced numerical modeling using RS2, the study assessed the structural integrity of mine slopes under current geometrical and geotechnical configurations.

The critical Stress Reduction Factors (SRF) obtained from five representative cross-sections (550, 750, 950, 1150, and 1350) ranged from 1.18 to 2.09, all exceeding unity and thus indicating overall stable slope conditions & benches are completely safe to operate in current geometry with stable critical SRF (>1). Section 950 exhibited the highest stability with an SRF of 2.09. However, the analysis revealed that Section 550, although having a relatively high SRF (1.95), also experienced the highest displacement (~1.9 m) and stress concentration (~87 MPa). This indicates that local deformation risks exist despite global stability, especially due to thick, weak alluvial deposits and geological discontinuities in this section. Section 550 showing much displacement and stress despite having crtitcal SRF of 1.95 signifies that with **current bench geometry working condition are safe but continuous bench monitoring is required in this part of mine**.

These findings underscore the importance of considering displacement and stress patterns alongside SRF values in slope stability evaluations. The study also confirms that the current bench geometry complies with DGMS guidelines, and no immediate safety threat exists in actively mined areas. However, as per current project report (PR), mine is expending in eastern direction and final bench cutting has been done at section 550 and no mine working is going in this portion so, there is no danger to man & machinery in worst case scenario. As per the above study daily bench monitoring near section 550 is strongly recommended as a precautionary measure, where stress & displacement are notable.

In conclusion, while the mine's slopes are currently **stable** under existing operational parameters, the presence of weak geological materials and variable hydrological conditions necessitate ongoing geotechnical surveillance. Integrating routine slope monitoring with periodic RS2 re-evaluation will ensure long-term slope integrity and operational safety in the challenging terrain of Bhanegaon OCM.

Recommendations. To ensure ongoing safety, it is advisable to enhance monitoring and possibly refine design in the critical sectors. In particular, Section 550's bench should be instrumented and surveilled closely. As the original study concludes, **"Daily bench monitoring near section 550"** is recommended.

A formal monitoring scheme could include inclinometers or extensometers installed on the slope face, and piezometers to track pore-water pressures in the alluvial cover. These instruments would detect any acceleration of displacement or rise in water pressure. In addition, periodic terrestrial laser scanning or photogrammetry surveys can quantify bench movements across the pit. If monitoring shows accelerating deformation, adaptive measures (such as reducing bench height, flattening slope angles, or dewatering) should be taken. Finally, further numerical analyses under varying scenarios (for example, fully coupled hydro-mechanical models to simulate rainfall infiltration) could provide insights into long-term stability trends. By combining these recommendations with strict adherence to DGMS safety factors, the Bhanegaon pit slopes can be managed safely even in the challenging ground conditions revealed by the RS2 study.

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8 PAPER PUBLICATION

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Stability Evaluation of an Opencast Coal Mine with Difficult Ground Conditions: A Case Study

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Abstract

Any nation's ability to grow is reliant on the expansion of its various industries, each of which adds to the GDP of the nation. With a 2.5 % GDP contribution, the mining industry is one of the major sectors. In mining, coal is an important and abundant fossil fuel in India, and it accounts for 55 % of the country's energy needs. The increase in coal production can be largely attributed to the rapid increase in open-cast mining activities and intensified mechanization. This has resulted in the opencast mines going deeper day by day with a maximum stripping ratio of 1:15, at a depth of about 500 m. For any opencast mine, a safe, properly designed, and scientifically engineered slope is essential for the economical, safe, and successful operation. In this paper, the stability evaluation of the pit slope at Bhanegaon Opencast Mine of M/s Western Coalfields Limited (WCL), which is centrally located Coalfields in India has been carried out. The loose and saturated thickness (20 m to 57 m) of the alluvial deposit (mixed with Black Cotton soil and sludge) with Kamthi series formation has high transmissivity which creates a stability problem. In this study, the slope stability analysis has been performed by using the computer program RocScience two dimension (RS2) to assess the effect of difficult ground conditions on stress distribution pattern and safety factor of pit slope. Sections were obtained by Terrestrial Laser Scanner (TLS) and analysed with the help of RS2 software. From the analysis, it was found that the Stress Reduction Factor (SRF) of sections where sand/clay band is present was less compared to other working areas because the cohesion of the upper layer material was less.

Keywords: Failure Analysis, Numerical Modelling, Shear Strength, Slope Failure, Stress Reduction Factor

1.0 Introduction

The majority of the coal production is done through opencast mines in India. Opencast mining is cost-effective mining method allowing a high grade of mechanization and large production. In India, the fast increase in the output of coal can be largely attributed to the rapid increase in opencast mining activities and intensified mechanization[1,2]. The production of coal during 2023-24 was 997.83 MT and import was 261.0 MT[3]. India's surface mining industry is expanding quickly in order to close the supply and demand imbalance for coal in the energy sector[4]. To access the economically valuable minerals beneath the surface, opencast mines require surface excavation as a result the stripping ratio reached 1:15 at 500 meters below the surface which caused the mines to get deeper every day. On a previously plain earth surface, the cut slopes must be formed to begin the excavation process. For safe and profitable mining, the cut slopes' stability is essential[5].

Slope stability is a major concern in opencast mines. To ensure safety throughout the mines' lifespan the safe mining operation is the responsibility of mine management. The making of the steepest pit slopes

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assuming they do not collapse during the mine's life. Therefore, when designing the deep open pit slopes, the design engineer must balance the two opposing components i.e., stability and steepness.

The stability of slopes is very important for safe mining operations. For stability, proper slope design based on the safety factors, correctly dealing with dynamic loading and water problems makes mine stable. The steepening of the slope could cause a slope failure, which would result in lost production, additional stripping costs to remove failed material, bench reforming, haul road rerouting, and production delays. On the other side, Steepening the slopes can result in significant cost savings.

If unsafe conditions are established, the Directorate General of Mines Safety (DGMS) may even decide to close the mine. As such, it is imperative to strike a balance between safety and economics. Consequently, there will be a correspondingly high amount of waste mining and dumping, which greatly increases the risk of highwall and slope failures. Because most production areas are located near the excavation floor, there is a constant risk to the personnel and equipment stationed there, which could result in a catastrophic loss of life and property.

It is necessary to analyse steep slopes thoroughly so that the entire process is safe and profitable. These days, open pits from both large and small-scale industries are unstable because they are reaching greater depths, which is a major concern when designing the slopes. For managing or preventing slope collapse, slope stability analysis and slope monitoring are very important[6]. Conventional approaches like limit equilibrium, kinematic analysis, and numerical methods are most frequently used to design slopes. These methods are practical and can be applied to various failure modes[1,7].

The limit equilibrium approach can be used to determine the factor of safety for predefined failure modes under homogeneous ground conditions[8]. Limit equilibrium techniques are often used by geotechnical engineers to analyse slope stability. These techniques compute a safety factor, which is the ratio of the available shear strength to the shear stress at equilibrium, with respect to the rock's (or soil's) shear strength. Their primary feature is their simplicity and low parameter count (hydrogeological conditions, geotechnical parameters, geological parameters, and slope geometry). However, complicated issues related to stability in open pit mines are frequently difficult to resolve using limit equilibrium techniques[9,10]. Several authors have worked on the Limit equilibrium method[11-14] but the development of numerical modelling through the Finite Difference, Finite Element, etc. methods give a better understanding of safety factor[15].

In this study, the authors have investigated Bhanegaon opencast mine for slope stability purpose, is situated in the Bina block of Kamptee Coalfields, this coal block falls in the Nagpur District of Maharashtra State (Figure 1). The Bhanegaon Opencast Project is a mine of Western Coalfield Limited (WCL) and situated in the northern part. This Project is located at the confluence of Pench and Kanahan Rivers. There is danger associated during mining operations due to river flowing from three sides of mining area. Considering multi seams and steep gradient of seams which falls in the range of 1 in 4.5 to 1 in 6, the Horizontal Slicing Method of mining is being used for Bhanegaon OCP (Bina). All types of Gondwana formation from the Talchir formation of Upper Carboniferous to the Kamthi formation of Upper Permian were encountered in Bhanegaon opencast project area during the geological exploration. The entire block is covered by a thick layer of Alluvium including Black cotton soil and river sand. The loose and saturated thickness (20 m to 57 m) of alluvial deposit (mixed with Black Cotton soil and sludge) with Kamthi formation having high transmissivity may create a stability problem. Currently mine is being worked as per DGMS guidelines and bench profiles are maintained accordingly. Bench geometry for alluvial soil is of 3 m height and 9 m width, for coal is of 10 m height & 10 m width and for rock mass is of 10 m height and 20 m width.

Figure 1. Bhanegaon mine location.

2.0 Field and Laboratory Investigations

2.1 Field Investigations

All types of Gondwana formations from Talchir Formation of Upper Carboniferous to Kamthi Formation of Upper Permian are present in Bhanegaon OCM. The Bina block is generally covered by a thick layer of black cotton soil and loose sand with pebbles (alluvium) followed by a blanket of Kamthis. None of the geological formations are exposed on the surface of the block. The geological structure is therefore based on the sub-surface data generated from boreholes (Figure 2 and Figure 3).

Figure 2. Bhanegaon mine benches.

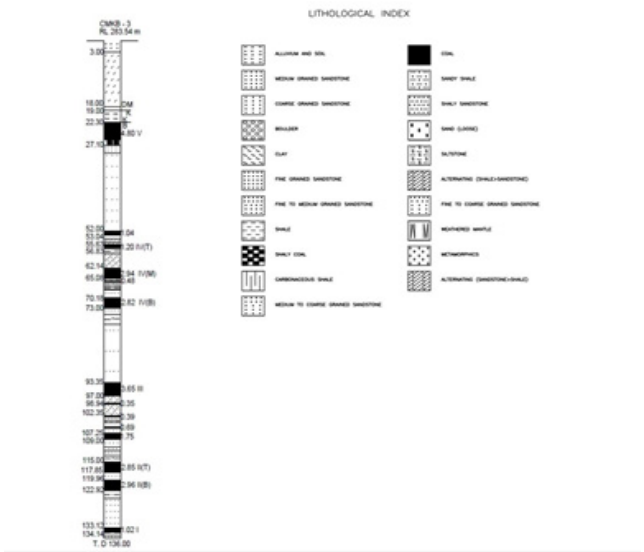

Figure 3. Borehole section and lithological index.

The drainage of the area is mainly controlled by the easterly flowing Kanhan River and Pench Rivers. The confluence of these two rivers is located just northeast of the block. A few seasonal nallahs originate within the block and drain into the Kanhan River. The Kamthi Formation along with Alluvial deposit (loose sand) represents the Shallow Aquifer. The thick bed of alluvium and current bedding seen in the mine cutting is indicative of recent alluvial deposition. Barakar Formation along with coal seam is lying below the Kamthi Formation/ Motur Formation represents the Deeper Aquifer. Water table was determined by Piezometric data.

2.2 Laboratory Investigations

In laboratory Density, Porosity, Poisson's Ratio, Young's Modulus (MPa), Peak Tensile Strength (MPa), Friction

Figure 4. Core cutting.

Figure 5. Core samples.

Table 1. Geo-mechanical properties of rock

Material Properties	Black Cotton	Alluvial Soil	Coal	Shale	Coarse Grain Sandstone	Medium Grain Sandstone	Fine Grain Sandstone
Unit Weight (MN/M^3)	0.015	0.018	0.015	0.020	0.018	0.020	0.021
Porosity Value	0.350	0.250	0.085	0.137	0.150	0.160	0.150
Poisson's Ratio	0.200	0.200	0.055	0.135	0.200	0.165	0.186
Young's Modulus (MPa)	10.000	20.000	1206.190	616.981	192.172	474.860	1051.400
Peak Tensile Strength (MPa)	0.050	0.100	2.290	1.800	0.384	0.785	1.137
Friction Angle (Degrees)	15.000	30.000	30.030	36.210	38.900	29.750	38.718
Cohesion (MPa)	0.050	0.020	18.663	13.326	8.424	12.110	29.300

Angle (Degrees), Cohesion (MPa) and Unconfined Compressive Strength were analysed by Stress-Strain analysis(IS 9221)[16], Brazilian Tenslile test(IS 10082)[17], triaxial test (IS 13047)[18], Porosity test (IS 13030)[19]. Samples of alluvial soil, black cotton soil, coal (from each coal seam) and sandstone (from coal seam parting) were collected from mine site to determine physio-mechanical properties. Samples against all 5 mine sections (Figure 6) were collected so that entire mine can be studied and analysed.

NX size cores were cut with Diamond core cutting machine (Figure 4 and Figure 5) and their properties were determined in the lab as mentioned in Table 1.

3.0 Numerical Modelling

To determine mine profile Terrestrial Laser Scanner (TLS) was used, and sections were created. Total 5 equidistance sections were created across the strike line to study the entire mine as these sections encompasses entire mining area (Figure 6). Sections are 550, 750, 950, 1150 and 1350.

For slope stability analysis models were created using the computer program RocScience two dimension (RS2). For model creation, first outer boundary was created with respective section co-ordinates and subsequently material layers were created with their properties as mentioned

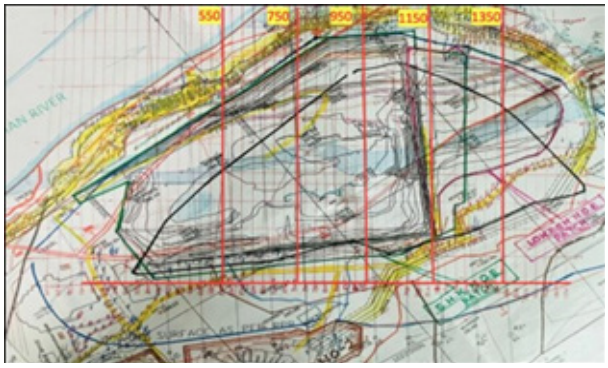

Figure 6. Mine plan with sections.

Table 2. Material and their colour representation in model

Material Name	Black Cotton	Alluvial Soil	Coal	Shale	Medium Grain Sandstone	Coarse Grain Sandstone	Fine Grain Sandstone
Material Color							

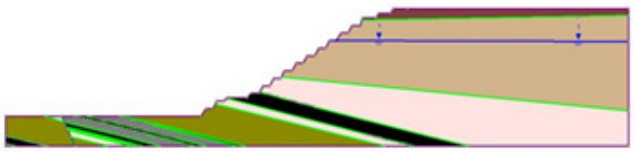

Figure 7. RS2 Model of section-1350.

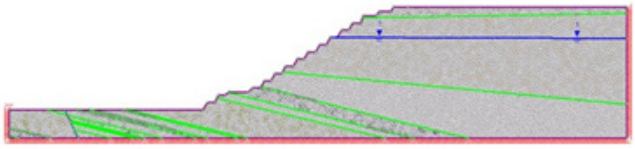

Figure 8. Model discretization and meshing.

in Table 1 (Figure 7). Details of different lithologies and their colour representation in models are shown in Table 2. Fault plane and Piezometric data were also used before Discretization and Meshing (Figure 8).

4.0 Results and Discussions

Stability of a mine section depends on a variety of factors including SRF, maximum displacement and maximum stress. A high SRF (>1) means that the structure is more resistant to failure, while a low SRF signals higher risk for collapse or movement. Maximum displacement helps identify areas where the mine section may be deforming excessively, signalling potential risks for instability. Monitoring and understanding the stress distribution is essential to prevent failure due to overstressed sections and to ensure that excavation activities do not introduce risks to stability. A low SRF combined with high displacement and high stress suggests that the mine section is at a high risk of instability. Conversely, a high SRF, low displacement and moderate stress would indicate a more stable condition.

The prepared models were analysed with maximum SRF tolerance 0.01 for precision in result. A small tolerance (0.01) would ensure more accurate Factor of Safety (FOS) by fine tuning the SRF value before failure occurs. After computation Critical SRF was determined with maximum displacement. At present mining operations are going smoothly without any safety disturbances as per DGMS guideline in soft material (106(4) of Coal Mines Regulations, 2017). Critical SRF obtained through RS2 modelling of sections 550, 750, 950, 1150 & 1350 are 1.95, 1.53, 2.09, 1.37 and 1.18 respectively, which showing the safe working conditions (Section 1350 shown in Figure 9).

In this analysis, all the sections were stable with more than one critical SRF (Figure 10). Further, the prepared sections were analysed based on their horizontal movement (displacement) and stress generated. Max.

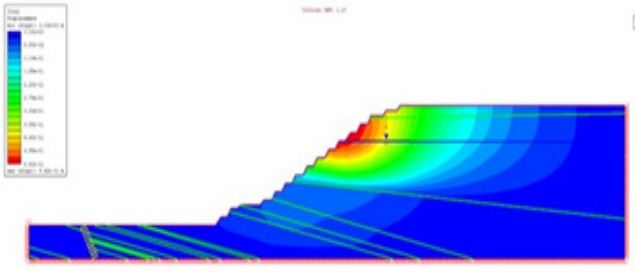

Figure 9. Critical SRF of section-1350.

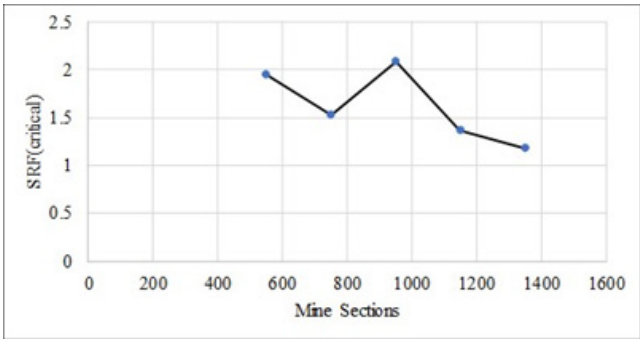

Figure 10. Critical SRF of all section.

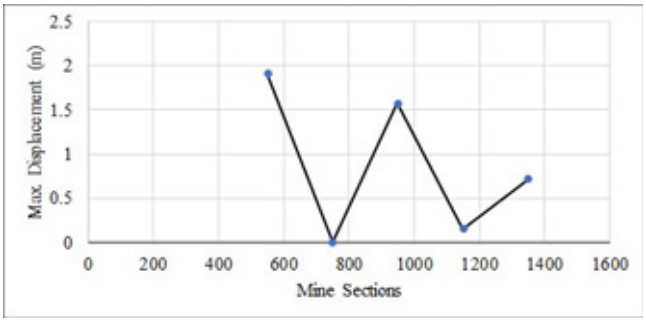

Figure 11. Max displacement of all section.

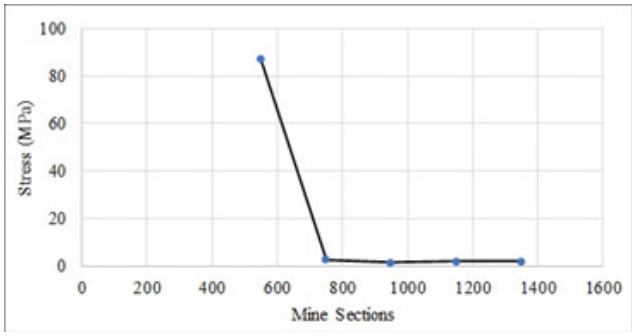

Figure 12. Max stress of all section.

displacement (meter) and max. stress (MPa) of sections 550, 750, 950, 1150, and 1350 are 1.900 and 87.38, 0.005 and 2.52, 1.570 and 1.33, 0.158 and 1.99, 0.718 and 1.83 respectively (Figure 11 and Figure 12). Section 550 (SW part of the mine) shows much displacement and stress due to geological discontinuity and higher alluvial cover as compared to the other part of mine.

5.0 Conclusions

In this study, the mine which was investigated had loose strata and water-bearing problems. Due to these conditions mine is very much prone to unstable but after analysing all the sections with difficult ground conditions (The loose and saturated thickness (20 m to 57 m) of alluvial deposit (mixed with Black Cotton soil and sludge) with Kamthi Formation) benches are completely safe to operate in current geometry with stable critical SRF (>1).

However, Section 550 showing much displacement and stress despite having critical SRF of 1.95 signifies that with current bench geometry working condition are safe but continuous bench monitoring is required in this part of mine. As per current Project Report (PR), mine is expending in eastern direction and final bench cutting has been done at section 550 and no mine working is going in this portion so, there is no danger to man and machinery in worst case scenario. As per the above study it's recommended to daily bench monitoring near section 550 as a precautionary measure.

6.0 Acknowledgements

Rock Samples were tested at Rock Mechanics Lab, VNIT and computer models were created by RocScience Software at computer lab, VNIT. Authors want to acknowledge efforts of Mr. Manoj Katole and Mr. Pramod Kubade, Technician, Department of Mining Engineering, VNIT, Nagpur in completion of this study. Authors also want to thank M/S Western Coalfields Limited (WCL).

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